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AUTOMATED PROCESS CONTROL FOR MACHINING (CAM)

JOSEPH DATSKO

DECEMBER 1979

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TECHNICAL REPORT

U.S. ARMY ARRCOM

MECHANICAL ENGINEERING DEPARTMENT
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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

Turning cuts were made on 4140 steel at 200 and 290 Brinell hardness with HSS and carbide tools. Computer programs were prepared for both Fortran and hand-held computers to calculate the cutting speed for turning. The programs were based on a Fundamental Machinability Equation that includes the tool material and shape, the size of cut and size of the workpiece. Programs were also written for surface finish and horsepower requirements, and for time and cost analyses and control. Test applications demonstrated capabilities, in quickly and accurately controlling machining rates for

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maximum production and/or minimum cost rates, far surpassing the use of contemporary handbook data and manual methods.

FOREWORD

This report was prepared by Joseph Datsko, Mechanical Engineering Department, The University of Michigan, Ann Arbor, Michigan, in compliance with contract DAAA08-78-C-0242 under the direction of the Engineering Directorate, Rock Island Arsenal, Rock Island, Illinois, with Mr. R. A. Kirschbaum as Project Engineer.

This project was accomplished as part of the US Army Manufacturing Technology Program and was administered by the US Army Industrial Base Engineering Activity. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army material.

TABLE OF CONTENTS

	Page
DD Form 1473 (Document Control Data R & D)	i
Foreword	iii
Table of Contents	iv
List of Tables	vi
List of Figures	vii
1. Introduction	1
1.1 Scope	3
2. The Fundamental Machinability Equation	4
2.1 The generalized equation	4
2.2 The fundamental machinability equation	7
2.2.1 Tool and environment constant	7
2.2.1.1 Tool life constant	7
2.2.1.2 Tool material constant	8
2.2.1.3 Effective rake angle constant	8
2.2.1.4 Cutting edge constant	9
2.2.1.5 Cutting fluid constant	10
2.2.1.6 Workpiece size constant	10
2.2.1.7 Surface condition constant	10
2.3 Work material constant	11
2.4 Size of cut constant	11
3. The Experimental Program	12
3.1 Equipment	12
3.2 Tool materials	13
3.3 Work materials	13
3.4 Experimental machining procedure	13
3.5 Experimental results	18
3.5.1 High speed tools	18
3.5.2 Tungsten carbide tools	21
3.5.3 Optimization of feed and speed	26
4. Computer Programs	32
4.1 Cutting speed-tool life programs	32
4.1.1 HP 67 programs	32
4.1.1.1 Preliminary instructions	32
4.1.1.2 Series A and B programs	33
4.1.1.3 Series C programs	35
4.1.1.4 HP 67 program preparation	37
4.1.2 Fortran program	45

Table of Contents

	Page
4.2 Surface finish programs	46
4.2.1 HP 67 programs	46
4.2.2 Fortran program	50
4.3 Horsepower requirements	55
4.4 Chatter and vibration	56
5. Optimization	59
5.1 Optimum tool life	59
5.1.1 The HP 67 program	59
5.1.2 The Fortran program	60
5.2 Optimum machining cost	60
5.2.1 Procedure for optimizing cutting conditions	63
5.2.1.1 Tool material	63
5.2.1.2 Tool shape	63
5.2.1.3 Depth of cut	65
5.2.1.4 Feed	65
5.2.1.5 Cutting Speed	65
5.2.2 The HP 67 program	65
5.2.2.1 The BtC program	65
5.2.2.2 The BtD program	66
5.2.3 The Fortran program	70
5.2.3.1 Instructions for operation of the program	71
5.3 Examples of cost calculations	72
5.3.1 Part number 10895621--piston tube	72
5.3.2 Part number 1200766--recoil cylinder	76
5.3.3 Part number 10895646--cylinder	76
5.3.4 Part number 10895646--cylinder--N/C	79
5.3.5 Part number 1207737--cylinder--N/C	79
6. Conclusions and Recommendations	83
References	84
Appendices	85
A. Cutting speed-tool life Fortran program	86
B. Equations for the theoretical surface finish	94

LIST OF TABLES

Table		Page
1	Cutting speed for turning 4140 steel	2
2	Tensile properties of 4140 steel of 197 Brinell hardness	14
3	Tensile properties of 4140 steel of 290 Brinell hardness	14
4	Effect of workpiece temperature on tool life	18
5	Job description of a turning operation	28
6	Data summary of Ramberg experiment	28
7	Unit costs based on the machinability equation	31
8	Programming steps for A-1 program	38
9	Programming steps for A-2 program	39
10	Programming steps for B-1 program	40
11	Programming steps for B-2 program	41
12	Programming steps for C-1 program	42
13	Programming steps for C-2 program	43
14	Programming steps for the surface finish program	48
15	Storage locations for the surface finish program	49
16	Programming steps for the Fortran surface finish program	51
17	Print out of a typical computer run	54
18	Programming steps for the horsepower program	57
19	Optimum tool life program	60
20	Programming steps for Btc series	67
21	Programming steps for BtD series	69
22	Machining cost for piston tube	73
23	Machining cost for piston tube	75
24	Machining cost for recoil cylinder	77
25	Machining cost for a cylinder	78
26	Machining cost for a cylinder on a N/C lathe	80
27	Machining cost for a cylinder on a N/C lathe	81

LIST OF FIGURES

Figure		Page
1	Effect of workpiece temperature on tool life	16
2	Effect of workpiece temperature on tool life	17
3	Effect of nose radius on cutting speed	19
4	Effect of nose radius on cutting speed	20
5	Effect of nose radius on tool wear (negative rake)	22
6	Effect of nose radius on tool wear (positive rake)	23
7	Effect of feed rate on tool wear	24
8	Effect of feed rate on tool wear	25
9	Effect of nose radius on cutting speed	27

AUTOMATED PROCESS CONTROL FOR MACHINING (CAM)

1. INTRODUCTION

Machining is the most expensive of all the manufacturing processes--more money is spent on machining in the United States each year than is spent on either welding, forming or casting. It was stated in the 1977 Report of the DOD/Industry Metal Chip Removal Conference that approximately 60 billion dollars are spent each year for metal removal from production parts. By optimizing each machining operation in industry, the national productivity can be improved when measured on the basis of either the quantity produced or the total cost. Consequently it is very desirable to optimize the machining operations and automate process control.

A machining operation is optimized when the cutting is done with the combination of speed and feed that results in a satisfactory part being produced at either a minimum cost or at a maximum production rate. A satisfactory part is one that has been produced with the correct tolerance and surface finish.

Most of the machining operations today are not being performed with the optimum combination of cutting speed and feed. The principal reason for this is the lack of a complete and reliable data base for the machinability of the metals being cut. The machining recommendations are too general to enable the NC programmer or the methods people to select the optimum cutting conditions for any specific job. By way of clarification, the typical machining data handbooks, with the exception of the old ASME Manual on Cutting of Metals, give a recommended "starting" speed for only one or two feed rates with only one tool shape for a particular metal. However, the combinations of feed, tool shape and economical tool life number in the hundreds for any one part being machined. In this case the optimum combination can be arrived at only through a lengthy and expensive trial and error method of recording the resulting production rates as the variables are changed one at a time. Because of the cost and inconvenience of this trial and error method, the search is usually terminated when the production rate is "satisfactory" rather than when it is optimum. Furthermore, variations in the material's properties from heat to heat or batch to batch can lead to a false determination of what the optimum conditions are over the long run.

This problem can be more easily understood by considering a specific example. It was specified by the sponsor of this machining project to study the machinability of the most commonly used metal at their facility, namely, 4140 steel at

hardness levels of 200 and 300 Brinell. Therefore, the material to be discussed in this example is 4140 steel at the above hardness levels. The data in Table 1 is a summary of the data given in the Machining Data Handbook [1] for turning with single point tools. The cutting speeds are those recommended for a 30 to 60 minute tool life.

TABLE 1. Cutting Speed for Turning 4140 Steel

Brinell Hardness	Depth (in)	Feed ipr	H.S.S. Tool	Speed fpm	Carbide Tool	Speed fpm
175 to 225	0.150	0.015	M-2	90	C-6	400
175 to 225	0.025	0.007	M-2	125	C-7	500
275 to 325	0.150	0.015	T-15	60	C-6	330
275 to 325	0.025	0.007	T-15	80	C-7	400

A careful engineering examination of the last two lines in Table 1 reveals the following deficiencies in data banks of this type. The discussion will center on the carbide tools only, since the comments for the high speed steel tools would be similar.

The first problem with this type of data bank is that it does not give any specific recommendation in regard to the effect that the hardness has on the permissible cutting speed. For a 0.150" depth of cut and a 0.015 ipr feed, a recommended cutting speed of 360 fpm is given for a range of hardness from 275 to 325 Brinell. Is the 360 fpm valid for the average hardness of 300, or is it intended for the minimum 275 Brinell hardness? If one batch of bars is at 275 Brinell and another batch has a hardness of 325, how much faster can the softer material be machined? As will be shown later in this report where the effect of hardness is discussed in conjunction with the Fundamental Machinability Equation 2 a bar of steel having a hardness of 275 Brinell can be machined with a speed approximately 20% higher than a comparable bar of 325 Brinell.

A second shortcoming to this type of data presentation is that the cutting speed is given for only two sizes of cut. In this case the two sizes of cut are 0.150" depth with a 0.015 ipr feed and a 0.025" depth with a 0.007 ipr feed. The user of this data is given no specific information in regard to what the cutting speed should be for any of the other hundreds of combinations of feed and depth that are normally used. It may be inferred that a higher speed could be used if the feed were reduced from 0.015 ipr to 0.010 ipr. But no specific, quantitative recommendation is given. One of the many advantages to the Basic Machinability Equation presented in this report is that it does give quantitative information regarding the effect of feed and depth of cut on the cutting speed. And by means of a computer or hand-held calculator the

answer can be obtained much more rapidly than by trying to find the answer in a handbook.

A third deficiency in the method of storing the machinability data as illustrated in Table 1 is that it does not give any information regarding how the cutting speed is influenced by the tool shape. The 360 fpm value given in the handbook is for a 0.150" depth of cut with a 0.015 ipr feed and a C-6 grade of carbide tool. But it doesn't state for what nose radius, rake angle, or side cutting edge angle the value pertains to. All three of these features of the tool shape, especially the nose radius, has a significant effect on the permissible cutting speed. For example, if the cutting speed for a given tool life is 360 fpm with a 3/64" nose radius, the cutting speed would have to be reduced to 300 fpm for a 1/64" nose radius or it could be increased to 390 fpm if a 1/16" radius tool were used. This gives a range of 30% in the permissible cutting speed for only a modest change in nose radius. If the rake angles and side cutting edge angles were also varied, the range of cutting speed would be even greater.

On the basis of the above discussions it is apparent that it is not feasible to create a complete data base of machining conditions by means of tabular information because it would require thousands of entries for just one metal. Consequently, the most practical and reliable data base for machinability is a Basic Machinability Equation that includes all of the machining variables associated with the work material, the tool material and shape, the size of cut, the size of the workpiece and the cutting fluid. Such an equation, along with computer programs for its solution, is presented in this report.

1.1 Scope. The objective of this project is to establish a computerized metal cutting matrix for machining operations and parts characteristics, according to general size and finish tolerances, with computer programs and tabular data for cutting parameters based on tests using a machinability equation. The system is designed to aid process and operation planners, N/C programmers, production supervisors, and estimators, and to provide data applicable in production scheduling and quality control. The foundation of the overall control system will be accurate determination and adjustment of specific machining parameters, with feedback to continually improve a required data base for overall process selection and control.

Major emphasis of the parts characteristics will be placed on material properties which will be correlated with material microstructure. The tests included the physical property determination and the machining of 4140 steel at Brinell hardness levels of 200 and 300. The machining was done with HSS and carbide tools having a variety of tool shapes in conventional turning. Formulas were written, tested, and programmed

for obtaining recommended machining speeds in both surface feet per minute and revolutions per minute for any feed rate and tool geometry. An equation and program were also prepared to relate the surface finish of the machined part to the cutting speed, feed rate, and tool geometry. The computer program was written in FORTRAN. In addition, programs were written and cards prepared for HP 67 hand-held programmable calculators so that the N/C programmers and production schedulers could take them right down onto shop floors as an aid in optimizing the machining conditions.

2. THE FUNDAMENTAL (OR BASIC) MACHINABILITY EQUATION [2]

Because of the extremely large number of combinations of machining conditions, the only workable data base for machinability information is one that includes in mathematical form the relationships of the following items to the optimum cutting speed: work material properties; tool material; tool shape; size of cut; size of the workpiece; cutting fluid. Such an equation was developed by the author[1] and experimentally tested on this project. As a result of the experimental data, some of the constants in the machinability equation were modified slightly to improve the accuracy and reliability of the equation. Each of the terms in the equation are defined and discussed in the following sections.

2.1 The generalized equation. In order to more readily understand the Fundamental Machinability Equation, it is beneficial to first consider it in the simplified form:

$$v_x = \frac{A \times B}{q} .$$

In this form, v represents the cutting speed in feet per minute and the subscript x denotes the tool life in minutes that should result from that particular cutting speed. Thus the notation v_{30} means the cutting speed that will result in a 30 minute tool life.

The constant A is a tool and environment constant. It contains all of the machining variables associated with the tool material, tool shape, and cutting environment such as workpiece size, scale condition and cutting fluids. It is the product of seven individual constants as explained in the following section.

B is the work material constant. It includes all of the physical properties of the material that influences or determines

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[1] Datsko, J., Material Properties and Manufacturing Processes, John Wiley and Sons, Inc., New York, 1966.

its intrinsic machinability based on the cutting speed--tool life criteria. The physical properties that must be used are not the room temperature values, but rather they are the properties of the material at the temperature in the chip formation region where most of the plastic deformation occurs during cutting. This temperature is approximately 600°F. It is not the tool-chip interface temperature, which is much higher.

The constant q is a size of cut constant. It illustrates the effect that the feed and depth of cut have on the permissible cutting speed. As explained in a following section, the magnitude of the effect made by changes in the feed is different for the various metals and actually depends upon the strain hardening rate of the metal.

The practicality and usefulness of this new generalized machinability equation can be demonstrated by comparing it to the Taylor equations that are so widely used both in Industry and Universities throughout the entire world. The most widely used form of the Taylor equation [3] is:

$$v = Kt^{-n}f^{-a}d^{-b}$$

where K, n, a and b are experimentally determined constants that vary with different work materials and tools. v is the cutting speed in fpm and t is the tool life expressed in minutes.

By letting the letter p represent the product $f^a d^b$, the Taylor equation can be written as:

$$v = \frac{Kt^{-n}}{p}$$

which is identical to form to the new Generalized Basic Equation:

$$v_x = \frac{A \times B}{q} .$$

Both equations have two terms in the numerator and a size of cut constant in the denominator. Therefore it is obvious that the Generalized Basic Equation is as convenient and simple as the Taylor equation. However, there are several disadvantages to the Taylor equation that are not present in the Basic equation. Consequently, the use of this new equation will result in a greater reliability of predicted cutting conditions and a more expedient way to determine the optimum cutting conditions for a specific machining operation.

The first disadvantage to the Taylor equation, from an engineering and scientific point of view, is the fact that the

constant K includes both tool material and work material properties in it. In order to understand and properly use mathematical equations that represent some physical model it is necessary that appropriate constants or terms be used in the equations. This means a separation of differing factors into separate constants. Thus one constant should represent the work material properties, another constant should represent the tool material, etc. This separation of constants is accomplished in the Basic equation. All of the work material properties that influence the material's machinability are included in the constant B. All of the tool material properties and tool shape are included in the constant A and are explained in the following section. Thus this separation of the machining conditions into meaningful constants gives the Basic equation the potential to be used in a more analytical and reliable manner than is possible with the Taylor equation.

The second disadvantage to the Taylor equation is that it assumes that the feed and depth of cut exponents a and b are constant for a given material and tool for all combinations of feed and depth. These exponents are definitely not constant for all sizes of cut, and this fact has been known for over forty years. The ASME Manual on Cutting of Metals that was [4] first published in 1939 contains hundreds of tables of cutting speed for depths of cut ranging from 1/32" to 1" and feeds varying from 0.002 ipr to 0.032 ipr for a variety of steels and tool shapes. These tables definitely show that the exponents a and b are not constant for all sizes of cut, but rather they decrease as either the feed or depth of cut increases. This second disadvantage of the Taylor equation is not present in the Basic Machinability Equation. The feed and depth of cut exponents in this new equation vary with the size of cut and thus give more reliable results.

The third shortcoming of the Taylor equation is that it neglects the influence that the strain hardening rate of a metal has on the feed versus permissible cutting speed relationship. The Basic equation has a term in it that accounts for the effect that the material's strain hardening rate has on the feed-cutting speed relationship. This acknowledges the fact that a certain change in feed does not have the same effect on a material such as cast iron or bronze, which has a zero strain hardening rate as it does on a material such as brass or stainless steel that has a large (0.5) strain hardening rate. Thus more accurate predictions and calculations can be made in optimizing machining operations when the strain hardening rate is included in the analysis.

A fourth shortcoming of the Taylor equation is that it is purely experimental and cannot be used to predict the machining conditions for any metal until actual machinability tests are conducted on that metal. This is due to the fact that the

constant K is an experimental "catch all" constant that does not show any relationship to the work material properties. One of the main advantages of the Basic equation is that because of the separation of the variables into meaningful constants, the constant B includes the important work material properties that influence its machinability. This makes it possible to predict the optimum machining conditions for any metal prior to the availability of actual experimental machinability data.

2.2 The fundamental machinability equation. The complete equation is too awkward and cumbersome to write out in its entirety, except when used in a computer program such as Fortran, so it is presented here in a modified form and each term is completely explained. In simple form the equation [2,5] is:

$$v_x = \frac{A \times B}{q}$$

where B is the work material constant, q is the size of cut constant and A is the tool and environment constant. Each is explained in the following paragraphs.

2.2.1 The tool and environment constant. The tool and environment constant A is the product of seven individual constants. It is represented as:

$$A = A_t \times A_m \times A_e \times A_c \times A_f \times A_h \times A_s.$$

The individual constants represent the following factors of the cutting conditions: A_t is the tool life constant; A_m is the tool material constant; A_e is the constant that accounts for the effect of the rake angles; A_c is the cutting edge constant that is influenced by the nose radius and side cutting edge angle; A_f is the cutting fluid constant; A_h is the constant that accounts for the effect that the size of the workpiece; A_s is the workpiece surface condition factor. The numerical values present in each of these constants were determined by studying much of the research data published during the past seventy-five years and by conducting some actual metal cutting tests during the project. These constants are all individually explained in the following sections.

2.2.1.1 The tool life constant. The tool life constant is the factor that determines the cutting speed that will result in the desired tool life. T1 and M2 tool materials were selected to serve as the basis for this constant. The equation for this constant is:

$$A_t = 30t^{-0.065}$$

where t is the expected tool life in minutes. However, if some

other high speed steel is used, then the proportionality constant 30 must be changed. For example, for a T-15 high speed steel tool material the constant must be changed to 33.

2.2.1.2 The tool material constant. At the present time there is very little documentation of the physical properties of the various carbide and ceramic tool materials, consequently, it is not possible at this time to relate the tool material constant to its physical properties. It is necessary to determine the value of the tool material constant experimentally by running some machining tests. This has been done for both C5 and C7 grade of carbide. See section 3.2 for an explanation of the carbide grades. The expressions for the tool material constants are:

$$A_m = 4t^{-0.14} \text{ for C5 carbide}$$

$$A_m = 4.5t^{-0.14} \text{ for C7 carbide}$$

The constants in these equations were determined from the actual machining tests with these tools on 4140 steel bars. Expressions for other grades of carbide can be determined experimentally by conducting a few machining tests.

2.2.1.3 The effective rake angle constant. The influence of the effective rake angle (ER) on the permissible cutting speed is a function of the hardness of the metal being cut [6]. In order to determine by how much a given effective rake angle influences the cutting speed, it is necessary to compare the actual effective rake angle to the "optimum" effective rake angle (ERO). The optimum effective rake angle is that rake angle which permits the highest cutting speed for a given tool life. The optimum effective rake angle can be determined from the equation [7]:

$$ERO = 46 - 0.1\ H_B$$

which was developed in part from the data given in the ASME Manual on the Cutting of Metals [4]. H_B is the Brinell hardness number of the metal at a temperature of 600°F. The temperature of 600°F must be used since that is the average temperature of the metal in the workpiece just ahead of the tool where most of the plastic deformation occurs. Thus, the optimum effective rake angle may be as large as 46° for a very soft metal such as pure aluminum, or it may be 0° or even a negative value for extremely hard metals.

The effective rake angle (ER) of a tool is a function of three angles that are ground on the tool point. These three angles are the side cutting edge (SCE), the side rake (SR),

and the back rake (BR). The effective rake angle can be calculated from the following equation:

$$ER = \tan^{-1} (\tan SR \times \cos SCE + \tan BR \times \sin SCE)$$

The effective rake angle constant A_e depends upon the ER/ERO ratio. Depending upon the numerical value of this ratio, A_e can be determined from one of the four equations below, which were developed by the author over the past 20 years and are included in reference [6].

1. $A_e = 0.9$ when the ER/ERO is less than -0.2.

2. $A_e = 1 + (0.6 - 0.001\ H_B) \times ER/ERO$ when the ER/ERO ratio is between -0.2 and 1.

3. $A_e = 1.8 - 0.00133\ H_B - (0.2 - 0.00033\ H_B) \times ER/ERO$ when the ER/ERO ratio is between 1 and 4.

4. $A_e = 1.0$ when the ER/ERO ratio is greater than 4.

2.2.1.4 The cutting edge constant. The length of the cutting edge is a function of the depth of cut and of the nose radius and side cutting edge angle. For a given depth of cut, the length of the cutting edge increases with an increase in either the nose radius or the side cutting edge angle. Also, for a given depth of cut the permissible cutting speed increases as the length of the cutting edge increases. The length of the cutting edge (LCE) can be calculated from the following equation which is derived from trigonometric relations:

$$LCE = R(1.571 - 0.017\ SCE) + [d - R(1-\sin SCE)]/\cos SCE$$

where R is the nose radius, d is the depth of cut and SCE is side cutting edge or entering angle expressed in degrees.

The effect of the length of the cutting edge for high speed steel tools is different from that of the carbide tools and therefore two relationships for the cutting edge constant A_c are given. The equation for HSS tools is in reference [6], and the equation for carbide tools was developed from actual machining tests and verified under this project.

For high speed steel tools the equation is:

$$A_c = (LCE/d)^{0.67}$$

and for carbide tools it is:

$$A_c = 4.38(LCE/d) - 2.38.$$

The nose radius has a larger effect on the permissible cutting speed for a carbide tool that it does for a high speed steel tool.

2.2.1.5 The cutting fluid constant. The cutting fluid constant is simply a ranking of the effectiveness of the three general types of fluids and dry cutting, or cutting with no coolant. In this ranking the water base cutting fluids serve as the basis for the rankings and are given a value of one. The numerical value of the cutting fluid constant A_f is given in the following table summarized from reference [6].

Fluid =	Water base	Light oil	Heavy oil	Dry
A_f =	1.00	0.90	0.90	0.85

These values are to be used with "flood" cooling, that is, when a copious supply of the fluid is directed to the tool-chip interface region. The values, except for dry cutting, have to be reduced slightly when only a small quantity of fluid flows by the tool-chip or tool-workpiece interface.

2.2.1.6 The workpiece size constant. The workpiece acts as a heat sink during machining. That is, it absorbs some of the heat that is created during the chip formation process. If the workpiece is large then the rise in temperature is small. However, if the workpiece is small, then the rise in its temperature during the machining operation can be very significant. The following relationship for the workpiece constant A_h indicates how much the permissible cutting speed is affected by the size of the part being machined.

$$A_h = (h/2)^{0.25}$$

where h is the radius of a solid bar, the wall thickness of a tube or the thickness of a plate being faced or milled.

The workpiece constant should be used in calculating the cutting speed only when no coolant is used, that is, for dry cutting. When a copious supply of cutting fluid is used, the constant A_h should be given a numerical value of one or else deleted from the calculations.

2.2.1.7 The surface condition constant. The surface condition constant A_s was not included in this program since this project was restricted to the machining of steel bars only. In this case the constant is equal to one. If cast surfaces were to be machined, then the value of the constant would be less than one, depending upon the kind of cast surface that was present.

2.3 The work material constant. The work material constant B includes those physical properties of the work material that determine its intrinsic machinability. The numerical value of the constant B can be calculated from the physical properties without the need of conducting the expensive metal cutting tests. The equation relating B to the material's physical properties is:

$$B = \frac{k}{H_B} \left(1 - \frac{A_r}{100}\right)^{0.5}$$

The thermal conductivity k has the units of BTU/hr ft °F. The Brinell hardness H_B must be the value obtained with a 3000 kg load for steel and a 500 kg load for soft non-ferrous metals. A_r is the area reduction, expressed as per cent, as obtained from a standard tensile specimen. All three of these properties must be the values obtained at a temperature of 600°F since that is the average temperature of the workpiece in the region where most of the plastic deformation occurs during machining. The derivation of this relationship can be found in an ASME paper [4] by Henkin and Datsko.

In most cases the numerical value of B alone is a reliable indicator of a material's machinability. This is particularly true when comparing the machinability of two metals for the same size of cut and with the same tool shape.

2.4 The size of cut constant. The size of cut constant q is a very important factor in determining the optimum cutting conditions for a given machining operation. The feed in a turning cut is probably the most important single variable that the machine operator or the NC programmer has at his disposal to influence the efficiency of the rate of metal removal. The relationship between the constant q and the feed is given in the following equation that is discussed in detail in reference [3]. The effect of the work material's strain hardening rate upon the numerical value of q is also included in the equation:

$$q = (f + y)^{a}(d + y)^{1-a}$$

where f is the feed in ipr, d is the depth of cut in inches, y is a strain hardening factor that is defined below, and a is an exponent that is a function of the actual feed to depth ratio as described below.

The strain hardening factor y takes into account the fact that during any machining operation on an annealed or heat treated part the tool is cutting through a work hardened layer after the first revolution. For example, when an annealed bar

is being turned on a lathe, a work hardened shoulder is generated on the bar after the first revolution; and from then on the tool is cutting through this hardened layer. The extent or magnitude of the resulting work hardening is a function of the material's strain hardening rate. For metals such as cast iron or bronze that do not work harden (m=0) the numerical value of y is zero and the size of cut factor is the same as in the Taylor equation. The following equation indicates what this relationship is.

$$y = 0.0055\ m^{0.5}$$

where m is the strain hardening exponent (rate) of the metal.

The numerical value of m for the 300 H_B 4140 steel tested in this project is 0.11. This results in a value of y equal to 0.002. The value of m for the 200 Brinell hardness 4140 steel used in this project is 0.23 which results in y equal to 0.0026. For light finishing or forming cuts, the value of y may be as large as the feed, and significant inaccuracies would be incurred if it were neglected.

The exponent a for the feed and depth of cut can be calculated from the equation:

$$a = 0.6(f/d)^{-0.05}$$

From this equation it can be observed that a is not really one fixed value for all feeds and depth of cut, but rather the numerical value of a depends upon the feed to depth ratio. For a cut having the feed equal to the depth, the value of a is 0.60. However, for a forming type of cut having a feed of 0.0005 ipr and a length of cutting edge of 2", the value of a is 0.90.

3. THE EXPERIMENTAL PROGRAM

3.1 Equipment. All of the machining tests were conducted on an 18 inch American Pacemaker lathe having a 15 horsepower variable speed drive motor. This made it possible to cut at any desired cutting speed expressed in surface feet per minute. Also, it permitted the cutting speed to be maintained at a constant value as the workpiece diameter was reduced. Standard negative and positive rake tool holders were used.

Tool wear was measured on both the flank and nose of the inserts by means of a Gaertner tool makers microscope. The maximum value for the width of the wear was recorded.

The tensile tests were conducted on a hydraulically loaded 60,000 lb Baldwin tensile testing machine. The testing was

done at a constant rate of loading of approximately 8,000 pounds per minute.

3.2 Tool materials. The high speed steel tools used in this project were 3/8" square of grade T-1 made by the Crucible Steel Company. They were ground to a variety of tool shapes in our own shop.

The carbide tools used in this study were triangular throwaway type 1/8" thick and with a 3/8" inscribed circle. Three different grades were used: Carboloy 350 and 370 and Kennametal K-45. The 370 grade corresponds to carbide association designation C-5, and the 350 and K-45 correspond to the designation C-7. Most of the cutting was done with negative rake tools and a few tests were conducted with positive rake. Nose radii of 0", 1/64", 1/32", and 3/64" were used.

3.3 Work materials. The work material reported on in this study is 4140 steel at two hardness levels. One hardness level corresponds to the annealed microstructure of ferrite and coarse pearlite with a Brinell range of 185 to 200. The second hardness level of approximately 300 Brinell corresponds to a high temperature tempered martensite microstructure. Tensile tests were conducted on 1 bar of material at these two hardness levels. The tensile specimens were 0.357" diameter and 2" gage length. Tests were conducted at both room temperature and at 600°F. The results are listed in Tables 2 and 3. Although several other steels were tested in this program, they were utilized only to determine the best cutting conditions and to check out the test procedures. Consequently the results of the tests on those materials is not included in this report.

The thermal conductivity of 4140 steel was determined to be 21.5 BTU/hr ft °F by means of a library search. The same value can be used for the steel at all hardness levels achieved by heat treating because the thermal conductivity, like the modulus of elasticity, is independent on the microstructure.

Based on the average values of hardness and area reduction at 600°F, the B value of the 4140 steel, having a room temperature hardness of 197 or 200, is calculated to be 0.125. The B value for the 290 Brinell steel is 0.077. These are the values that are used in the computer programs included in this report.

3.4 Experimental machining procedure. Machinability tests were first conducted on 1045 and 4340 steel that was immediately available from a previous research project. The purposes of these preliminary tests were twofold: first, to generate some experimental data that could be used to check out the format of the computer programs; second, to establish the

TABLE 2

Tensile Properties of 4140 Steel of 197 Brinell Hardness

	Room Temperature			600°F		
	Long.	Trans.	Ave	Long.	Trans.	Ave
S_Y	46	46	46	----	----	----
S_u	95	95	95	86	89	87
m	.23	.23	.23	.158	.181	.170
σ_o	169	167	168	138	145	141
A_r	54	17	36	32	16	24
H_B	---	---	197	----	----	150

S_y, S_u and σ_o are in ksi. Long = longitudinal, Trans. = Transverse.

TABLE 3

Tensile Properties of 4140 Steel of 290 Brinell Hardness

	Room Temperature			600°F		
	Long.	Trans.	Ave	Long.	Trans.	Ave
S_y	93	96	95	----	----	----
S_u	132	131	132	138	136	137
m	.110	.105	.107	.158	.123	.141
σ_o	188	185	186	220	202	211
A_r	39	21	30	26	14	19
H_B	----	----	290	----	----	250

cutting conditions that would be used as the "standard" conditions for the remainder of the project when the 4140 steel would be tested.

The standard cutting conditions selected were a feed of 0.008 ipr and a depth of 0.090". These values would make the best use of the limited amount of steel that could be machined under this project. A limited number of cuts were also made with feeds of 0.016 ipr and 0.004 ipr to check out the feed effect that is built into the computerized machinability equation.

Tool wear was measured periodically during each machining test. This was done by stopping the cut and measuring the nose and flank wear on a tool maker's microscope. The test was continued until the wear exceeded 0.020". That value of wear was selected as the point of failure for the carbide tools because with a slightly larger wear land the surface finish of the workpiece would begin to deteriorate. In the case of the high speed steel tools, the measure of tool life was the complete failure of the cutting edge.

During the early part of the experimental tool life testing, it was observed that the temperature of the workpiece increased as successive cuts were made on it and the diameter was reduced. By the time a 4 inch diameter bar was machined to a 2 inch diameter, the temperature of the bar increased by approximately 100°F. It was decided at that time to see if such an increase in the workpiece temperature would affect the cutting speed-tool life relationship. A series of tests were run on bars of steel while keeping the bars at room temperature. This was accomplished by cooling the bars with a stream of coolant applied in such a manner that none of it came into contact with tool-chip interface zone. A second series of tests were conducted in which the same bars were first preheated in a furnace. It was found that the cutting speed-tool life curve was significantly lower for the warm bar than for the one machined at a constant temperature of about 80°F. The results of these tests are summarized in Table 4 and Figs. 1 and 2. As a result of these tests, all of the machinability data collected for 4140 steel in this study were obtained by keeping the workpiece at a temperature range between approximately 80 and 100°F.

The surface finish was measured with a profilometer and also by comparing the machined surface to a series of surface finish standards especially made for this project. A computer program was written based on a derived equation of the relationship of the surface finish to the tool shape, the feed, and the cutting speed. The derivation and the program are included in the Appendix B.

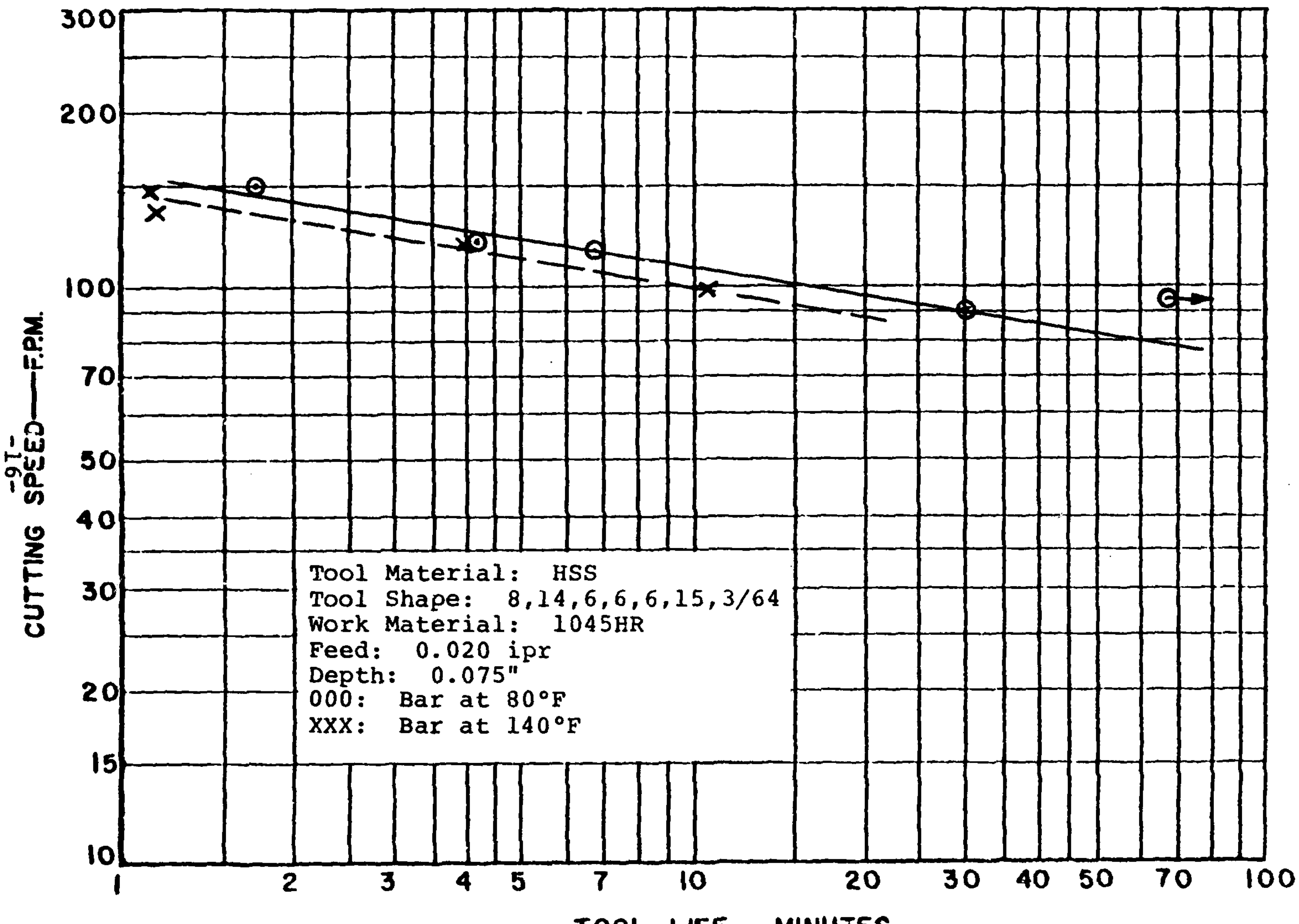


Fig. 1. Effect of Workpiece Temperature on Tool Life.

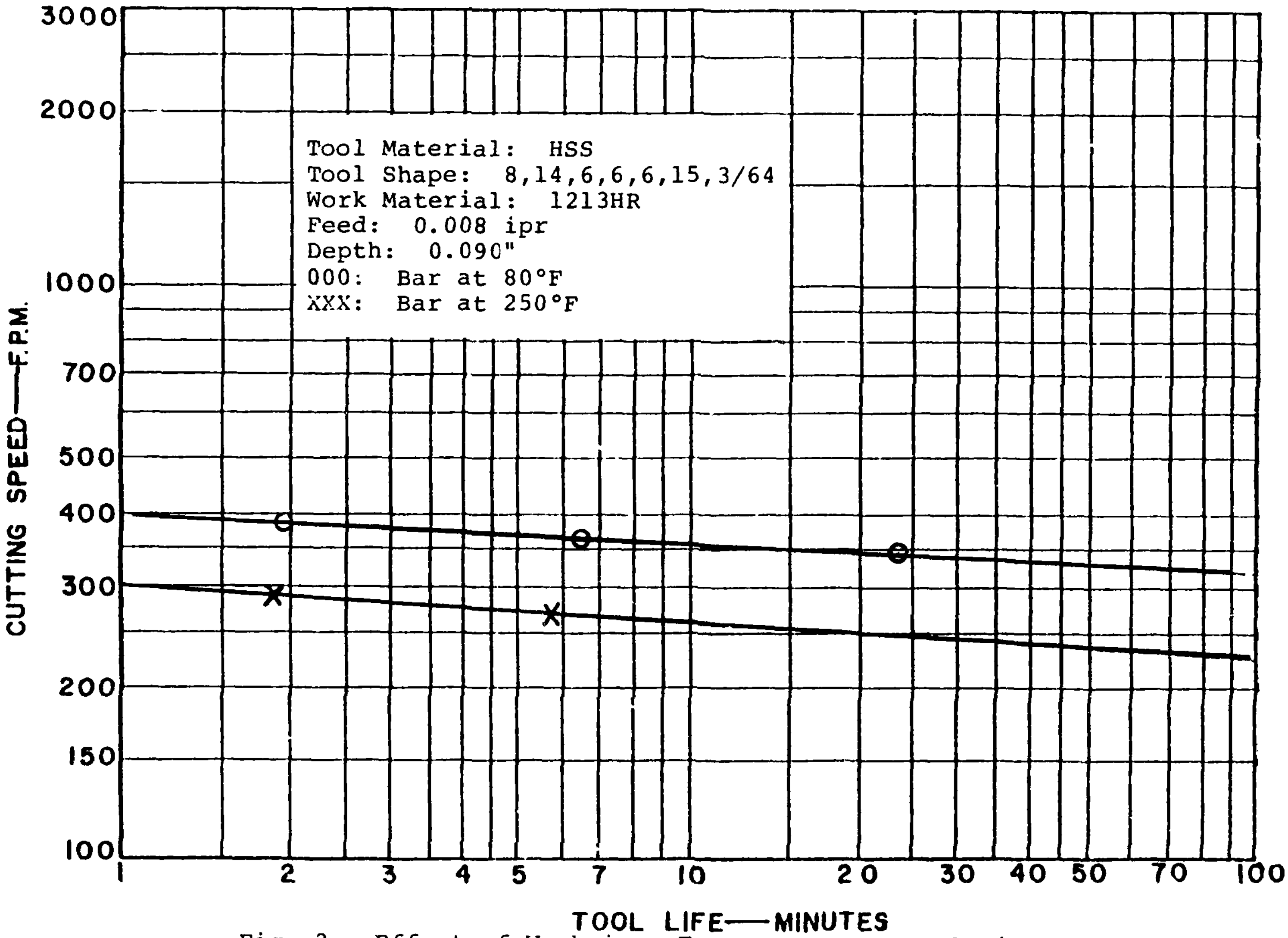


Fig. 2. Effect of Workpiece Temperature on Tool Life.

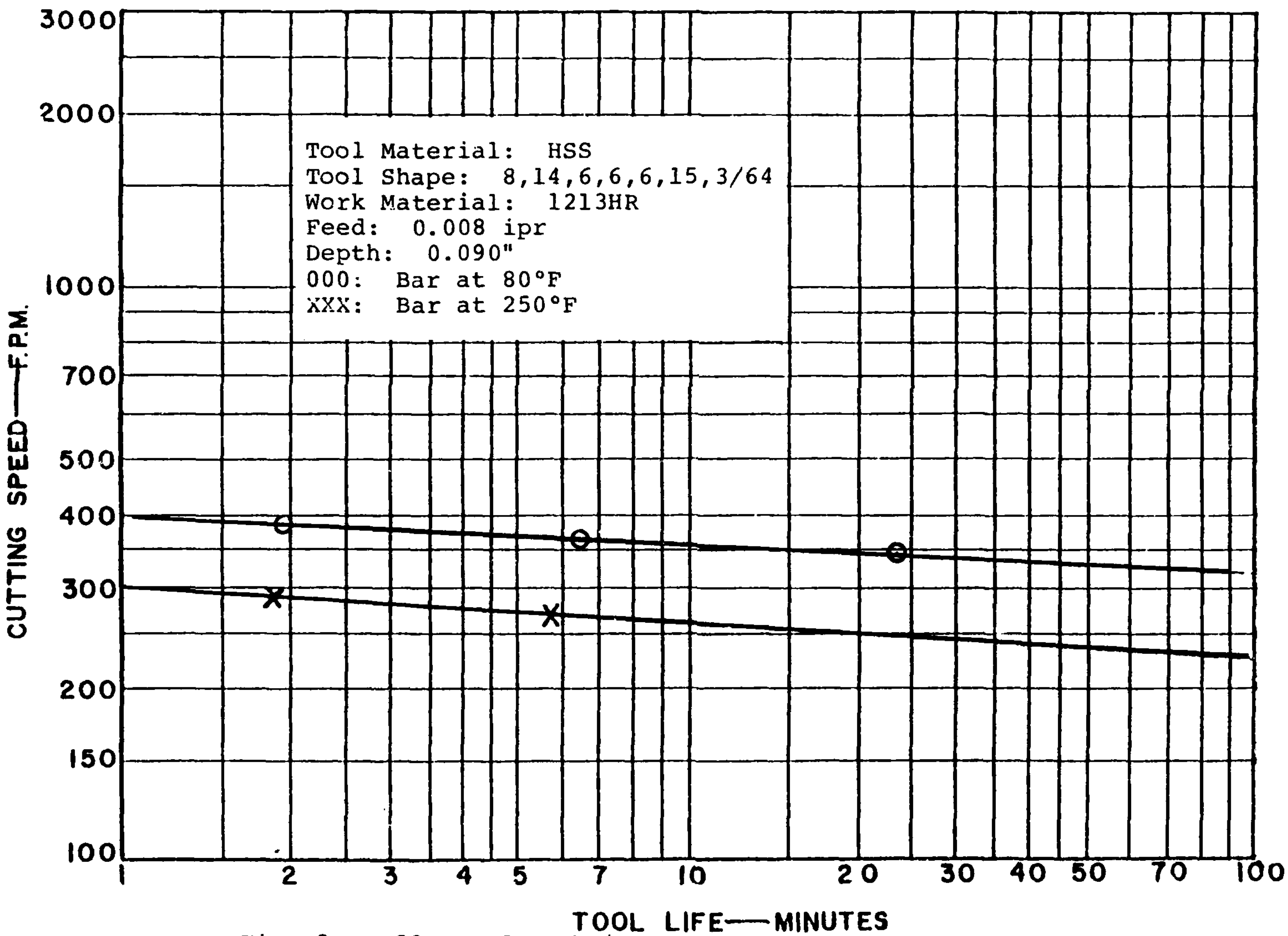


Fig. 2. Effect of Workpiece Temperature on Tool Life.

TABLE 4

The Effect of the Workpiece Temperature on Tool Life When Turning With HSS Tools

Steel	Depth	Feed	Speed	Tool Life: Room Temperature	140°F	250°F
1045	.075	.020	100 fpm	25 min.	9 min.	---
1213	.090	.008	300 fpm	40 min.	---	0.1 min.

3.5 Experimental Results

3.5.1 High speed steel tools. The results of the machinability tests with the high speed steel tool material is shown in Figs. 3 and 4 for the 190 Brinell hardness and the 290 Brinell hardness, respectively. Both of these figures show the increase in nose radius. The results shown here are in general agreement with the results published in the ASME Manual of Cutting Metals [4] and in O. W. Boston's Metal Processing [6].

One interesting result of these tests is the verification that the slope n of these cutting speed-tool life curves is 0.065. This value is lower than that reported in the research literature prior to 1950, but is in agreement with the results obtained on many other tests with high speed steel tools during the last twenty years. This difference may be due to changes in the manufacture of the tool material that occurred during this time, or it may be due to more exacting methods of conducting the machinability tests.

The results obtained with the high speed steel tools were very close to the results expected based on the original Fundamental Machinability Equation. In fact, the only modification required in the original equation

$$A_t = 25t^{-0.08}$$

was to change the two constants slightly to

$$A_t = 30t^{-0.065}.$$

It is the latter equation that is built into the computer programs.

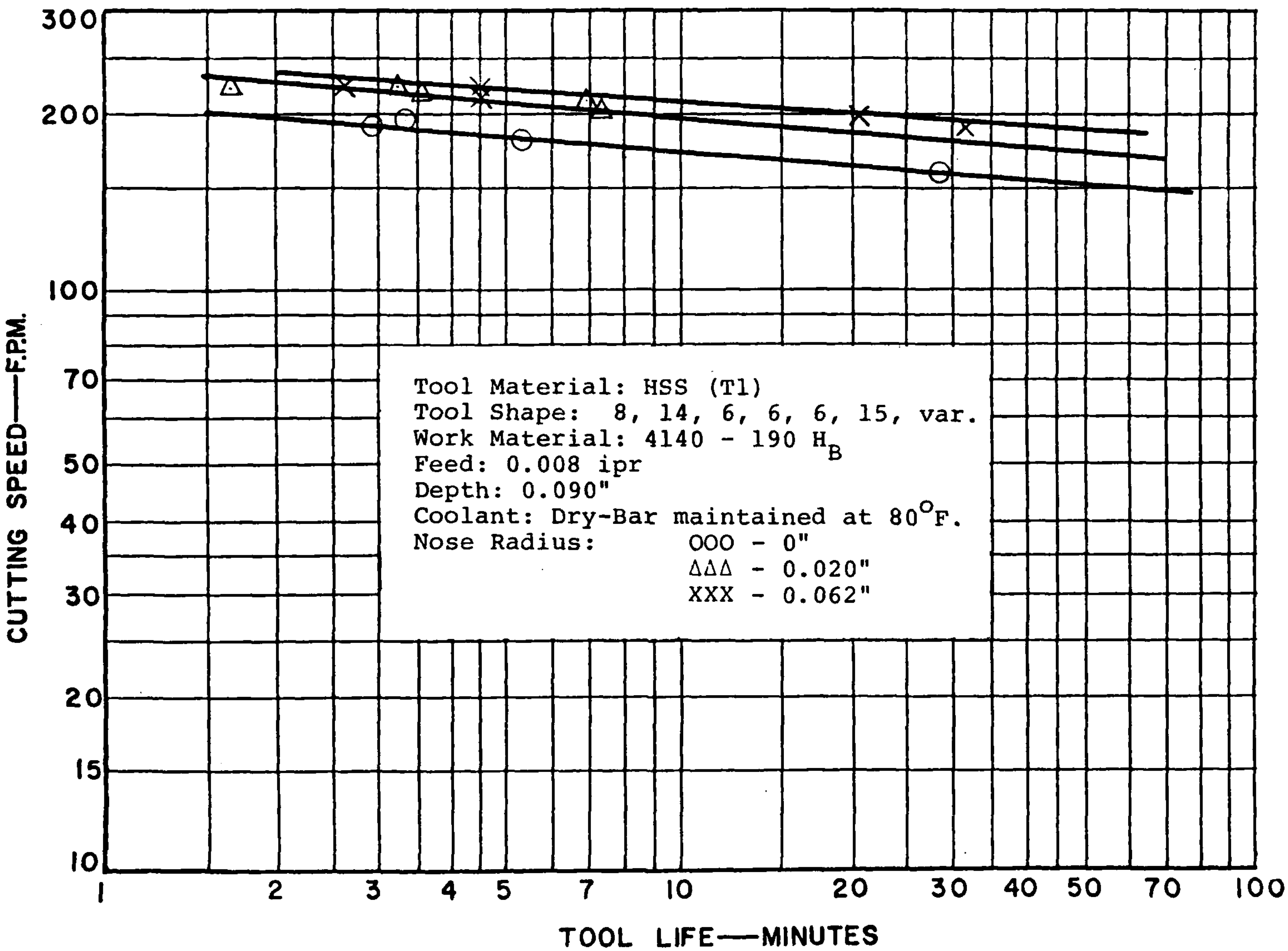


Fig. 3. Effect of nose radius on cutting speed.

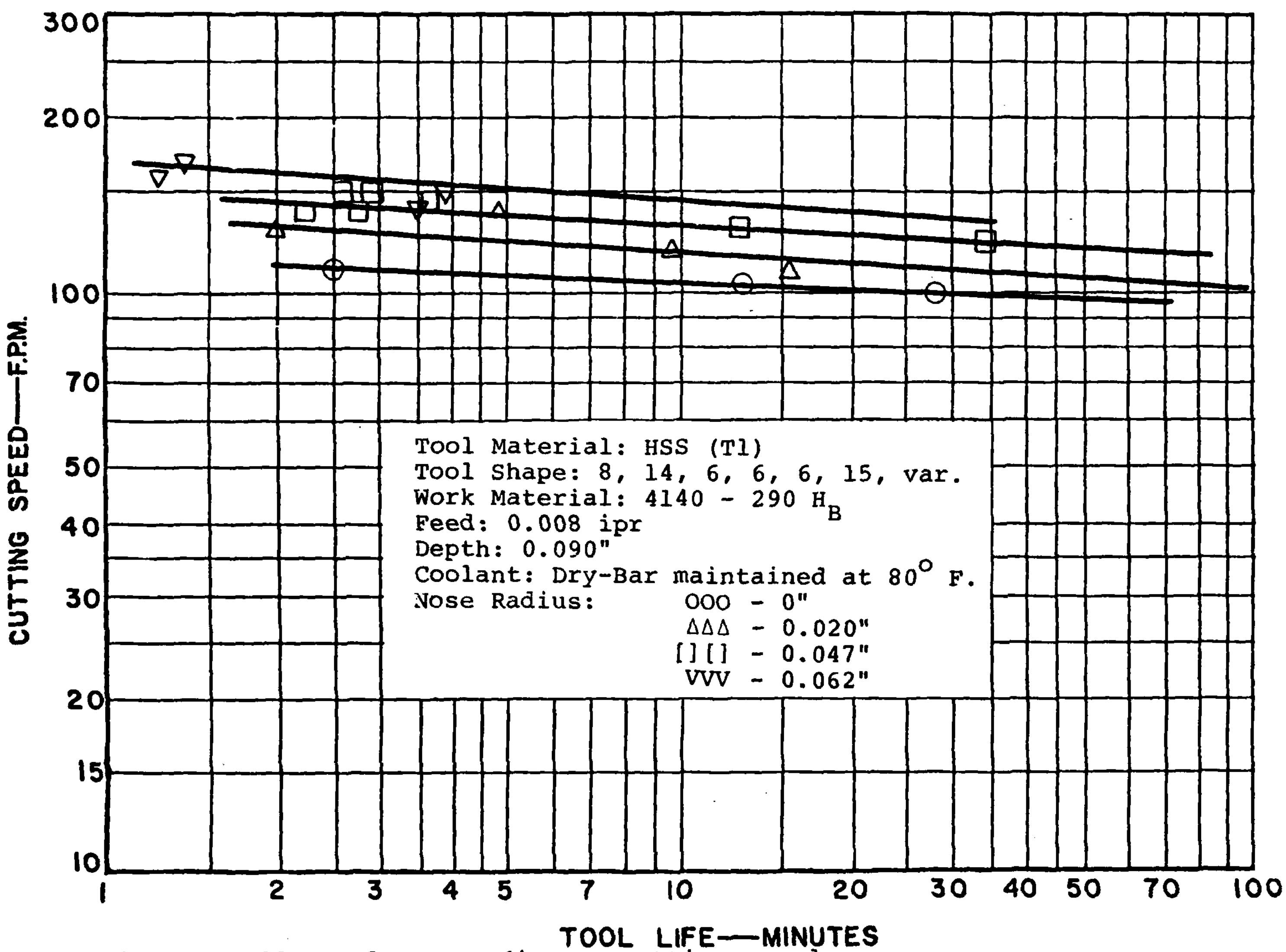


Fig. 4. Effect of nose radius on cutting speed.

3.5.2 Tungsten carbide tools. The experimental determination of the machinability of metals when carbide tools are used is much more involved and time consuming than when high speed steel tools are used. This condition is due to the fact that tool life for carbide tools is defined as the cutting time necessary to create a certain specified length of wear land such as 0.010, 0.020, or 0.030 inches. In order to determine what the value of the tool life (expressed in minutes) is, it is necessary to periodically stop the cutting, remove the tool, measure the length of the wear land, record both the time and wear, and then continue the test. Figures 5 through 8 show the results of such tool wear tests.

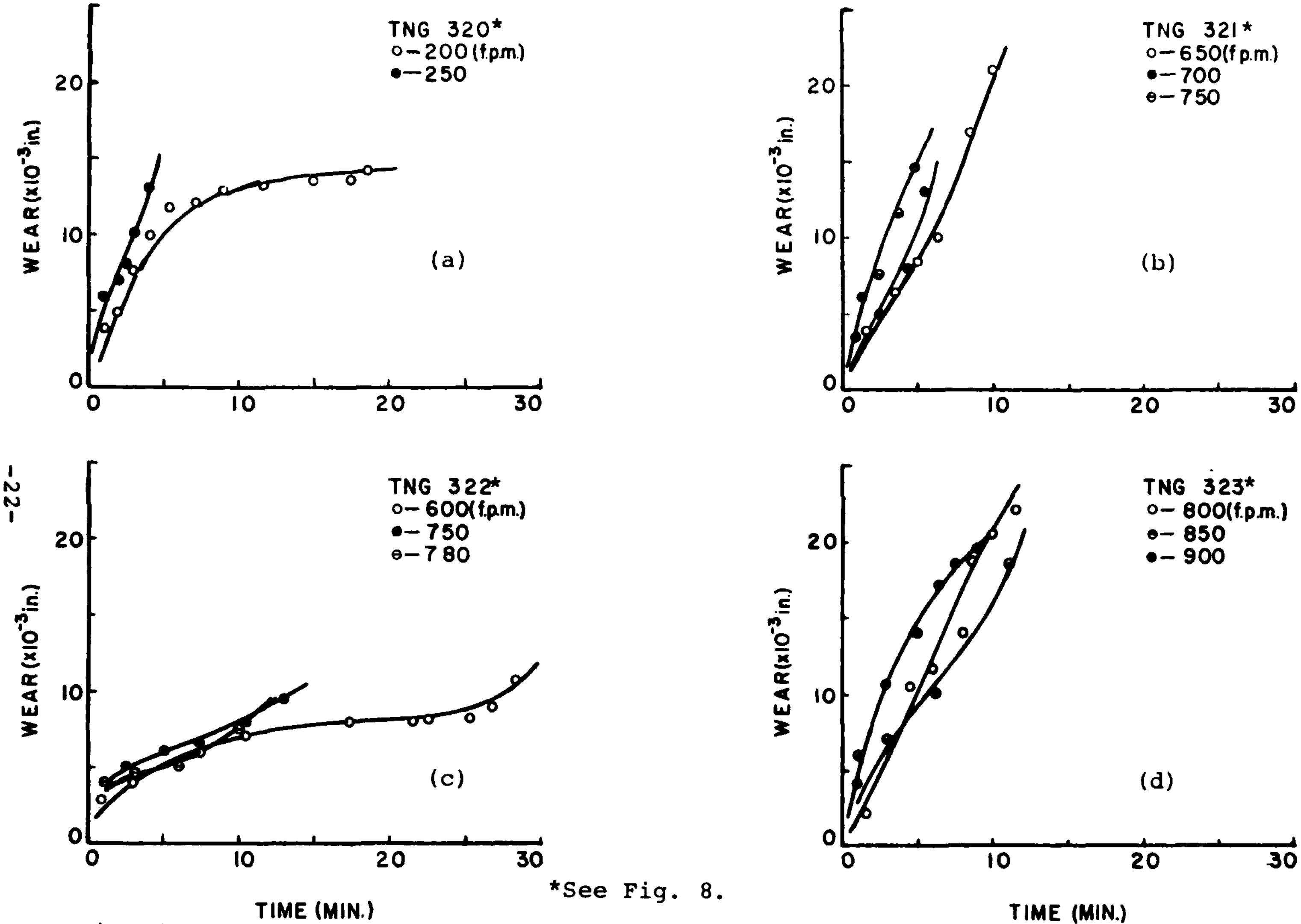
Figure 5 illustrates the effect of the nose radius on tool wear when cutting 4140 steel of 290 Brinell hardenss at a variety of cutting speeds. Due to the limited amount of work material available some of the tests run at the lower cutting speeds had to be discontinued before the wear reached 0.020", the value of wear selected as the basis of defining tool life in this project. In these cases, the curves were extrapolated to give the expected tool life. Negative rake tools were used in these series of tests.

Figure 6 shows the effect of nose radius on tool wear when a positive rake tool is used. The material in this case was 4140 at 190 Brinell hardness. The upper left pair of curves compares the positive rake tool to an identical negative rake tool. As can be seen, the positive rake tool is superior in that it requires approximately eight minutes to obtain a 0.020" wear compared to six minutes for the negative rake tool. The remaining 3 sets of curves in Figure 6 illustrates the effect of the nose radius on tool wear.

Figure 7 illustrates the effect of the feed rate on tool wear when machining 4140 steel of 197 Brinell hardness. Feeds of 0.004, 0.008, and 0.016 ipr were used. The results obtained here are in general agreement with the results published in the research literature during the past twenty years.

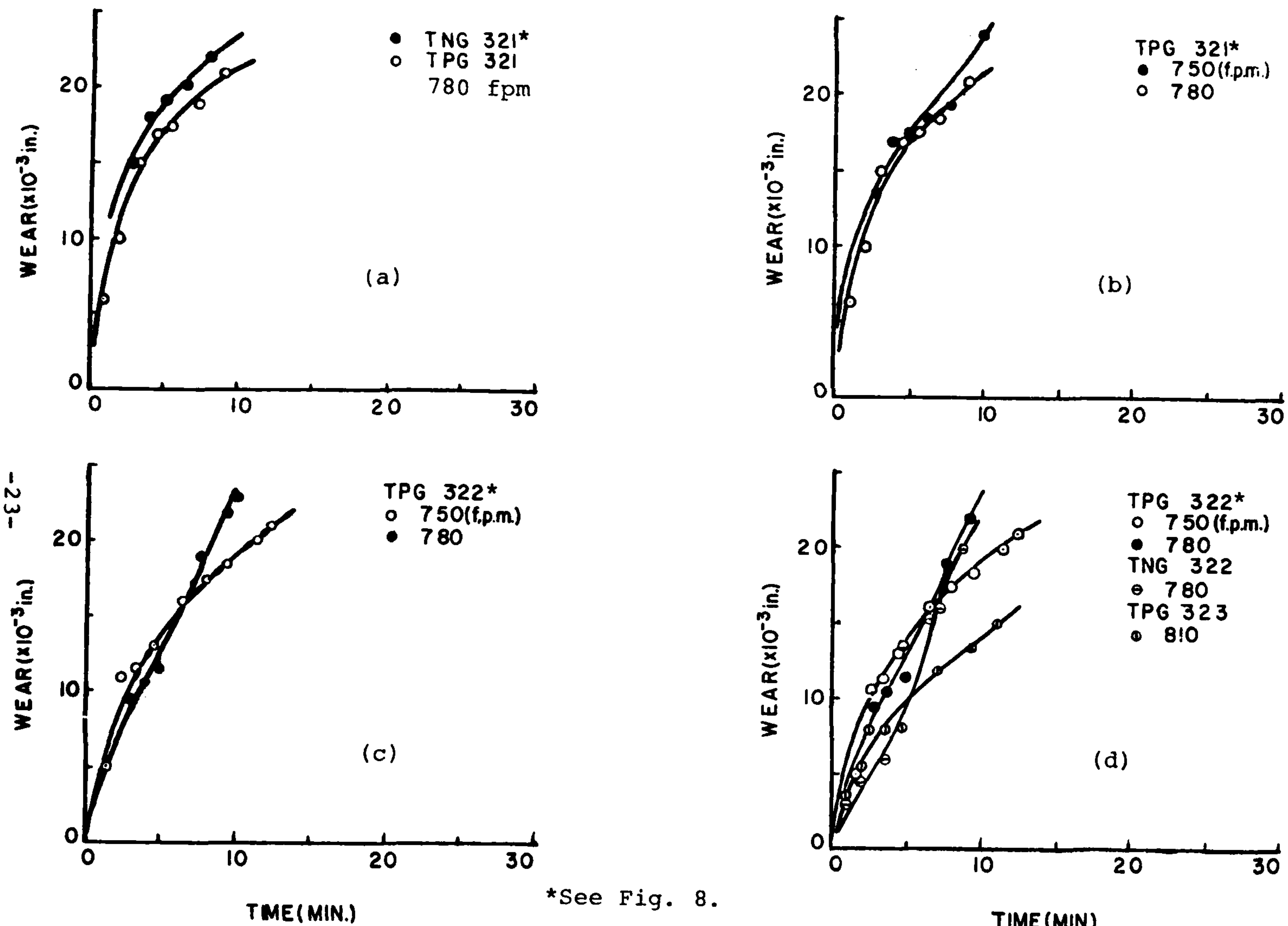
Figure 8 is similar to Figure 7 except that a 1/64 inch nose radius was used instead of the 1/32 inch nose radius.

The cutting speed-tool life points corresponding to a 0.020" wear land are drawn in Fig. 9. Figure 9 illustrates the effect that the nose radius has on the cutting speed for a given tool life. It should be noted how poor the performance of a zero nose radius tool is compared to the 1/64" nose radius tool. Increasing the nose radius to 1/32" and 3/64" permits a considerable increase in the cutting speed for a given tool life. Both the slope of these curves and the relative effect of the nose radius on the cutting speed is in general agreement to values found in the published literature.



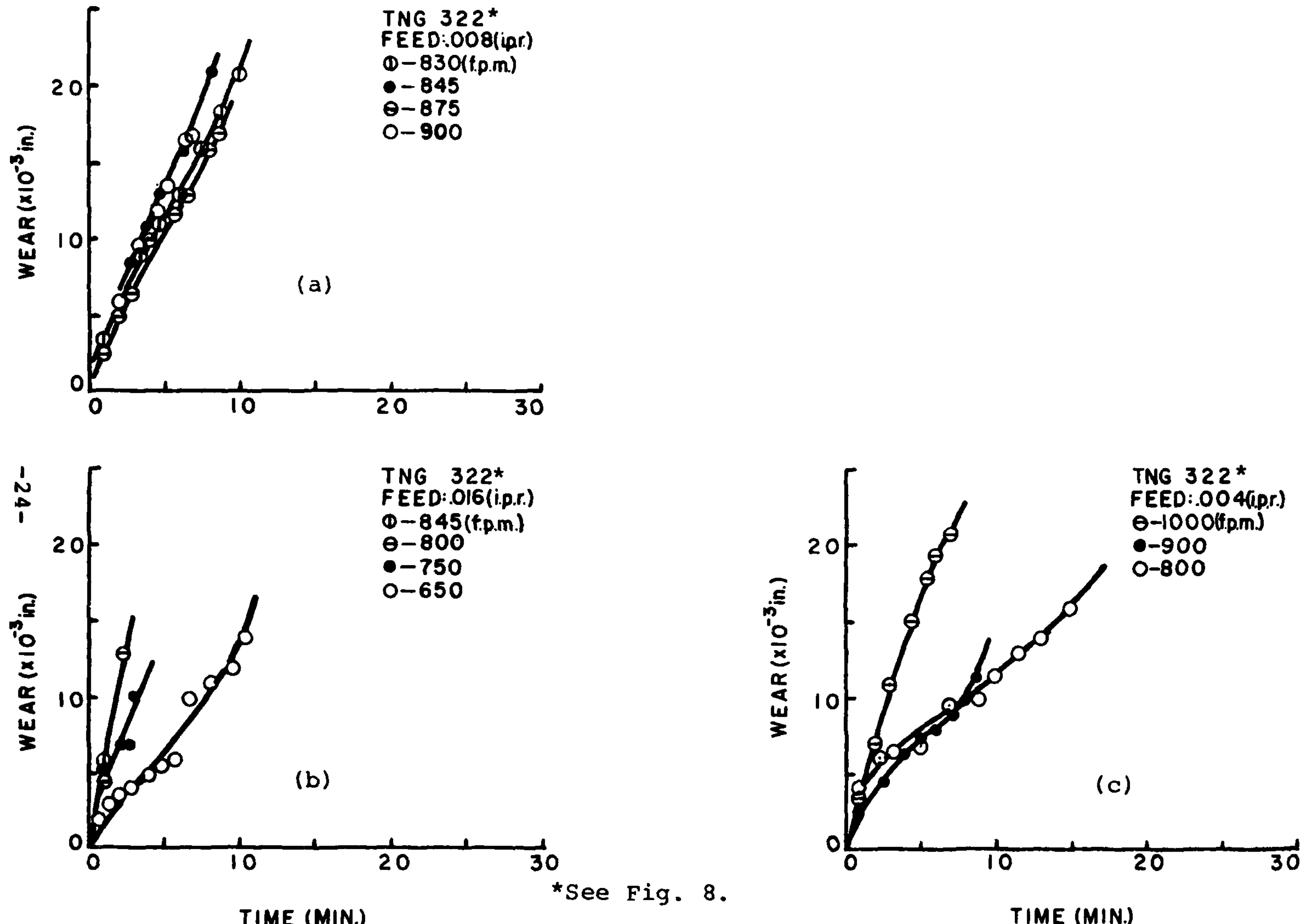
*See Fig. 8.

Fig. 5. Effect of Nose Radius on Tool Wear with Negative Rake. Work Material is 4140 Steel at 290 Brinell.
Nose Radius: Fig. a = 0", b = 1/64", c = 1/32", d = 3/64".
Side Cutting Edge Angle = 0.



*See Fig. 8.

Fig. 6. Effect of Nose Radius on Tool Wear with Positive Rake. Work material is 4140 Steel at 190 Brinell. Figure a Compares Negative Rake to Positive Rake. Figures b, c, and d Show the Effect of Nose Radius. SCEA = 0.



*See Fig. 8.

Fig. 7. Effect of Feed Rate on Tool Wear. Work Material is 4140 Steel at 197 Brinell. SCEA = 0. a = 0.008 ipr, b = 0.016 ipr, c - 0.004 ipr.

*TNG: Triangular, Negative, Ground
*TPG: Triangular, Positive, Ground
*xyz: x = inscribed circle in 1/8"
y = thickness in 1/16"
z = nose radius in 1/64"

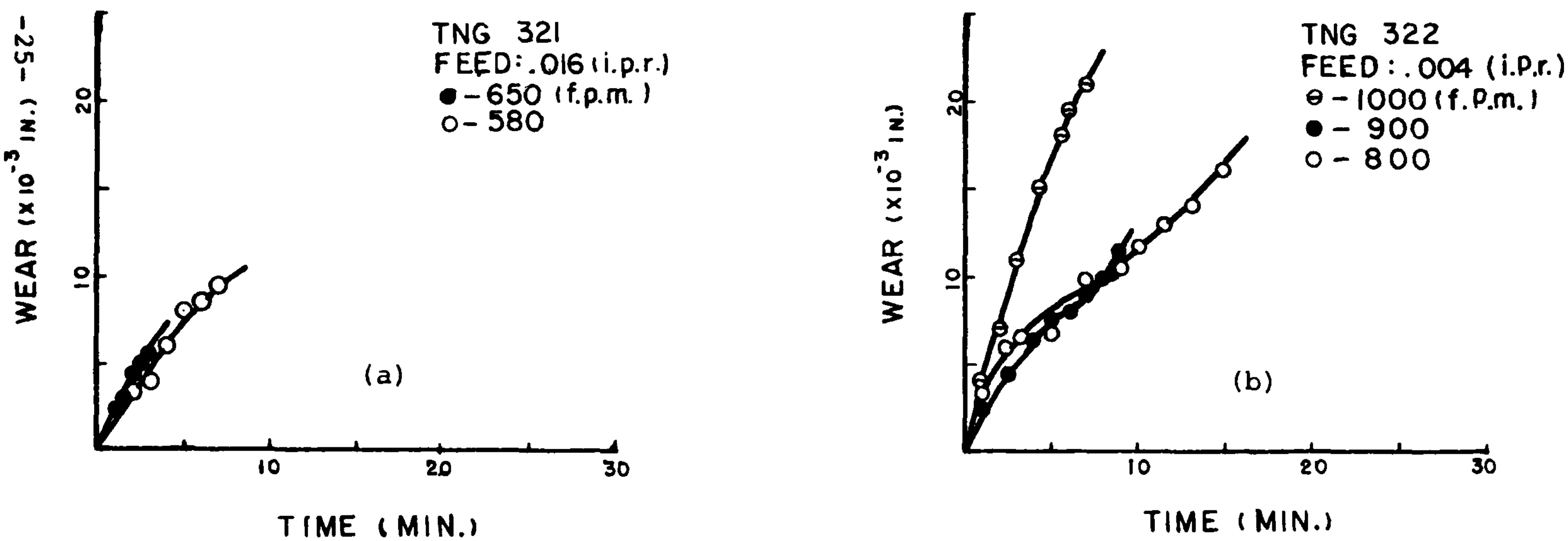


Fig. 8. Effect of Feed Rate on Tool Wear. Work Material is 4140 Steel at 200 Brinell. SCEA = 0. a = 0.016 ipr, b = 0.004 ipr.

Comparisons between the performance of positive rake and negative rake tools can be made from Fig. 6a. It can be seen that for the cutting speed of 780 fpm the negative rake tool (TNG 321) achieves 0.020" wear in about 6 minutes while it requires about 8 minutes for the positive rake tool (TPG 321) to reach the same wear. Because of the limited amount of material available at each hardness level it was not possible to make direct comparisons between negative and positive rake tools for all of the wear tests conducted. For example, Figs. 6b, 6c, and 6d show the effect of nose radius on tool wear for positive rake tools and Figs. 5a, 5b, 5c, and 5d do the same for negative rake tools. However, in the former case the steel was 190 Brinell and in the latter case it was 290 Brinell.

The data from the tool wear curves were used to draw the tool life lines in Fig. 9. The tool life was selected as the time required to obtain a 0.020" maximum wear on the flank of the tool. It is very apparent from the data shown here that a 0" radius carbide tool is very inefficient. Increasing the nose radius from 0" to 1/64" (0.016") permits the cutting speed for a 10 minute tool life to be increased from 220 fpm to 650 fpm. Increasing the nose radius to 3/64" (0.047") permits the speed to be further increased to 900 fpm.

An analysis of the data in Fig. 9 revealed that the effect of the nose radius on the permissible cutting speed could be represented by the equation

$$A_c = 4.38(LCE/d) - 2.38$$

which is discussed in section 2.2.1.4 of this report.

3.5.3 Optimization of feed and speed. A modified matrix or analytical method of determining the optimum feed and speed for a particular part on a specific lathe using The Fundamental Machinability Equation is presented in this section. In order to compare the results and benefits of selecting feeds and speeds by the traditional statistical matrix method with those obtained by using the analytical method, the same job description (machining operation) given in Table 2.5 of the 1974 Ramberg Report [7] will be used here. These conditions are listed in Table 5.

The Ramberg experiment selected a matrix consisting of three speeds (192, 220, and 255 rpm) and three feeds (0.0168, 0.0187, and 0.021 ipr). The results of their experimental study are summarized in Table 6.

The optimal feed-speed combination is selected as the one having the lowest unit cost, CU. In this case it is 255 rpm and 0.0168 ipr.

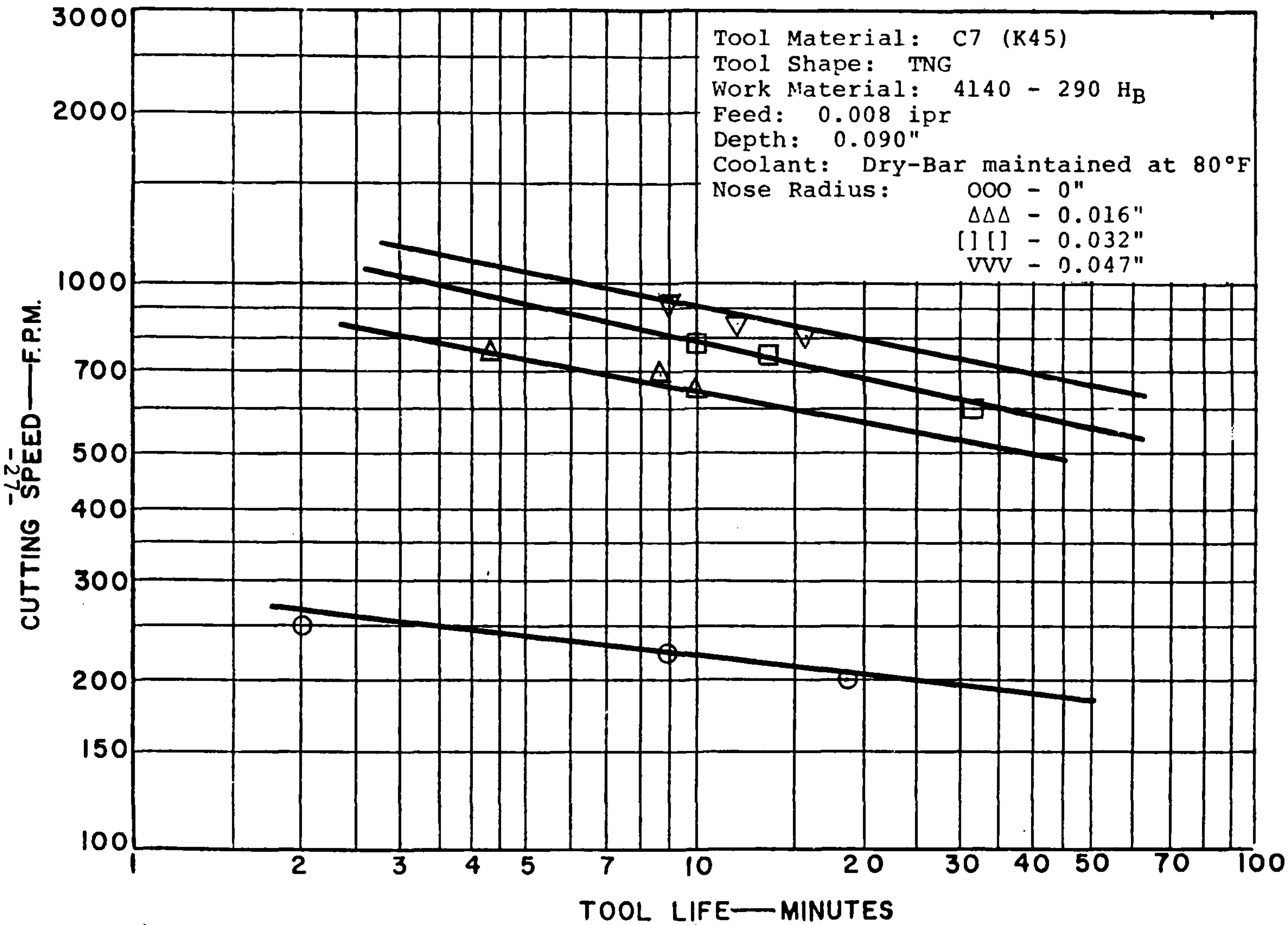


Fig. 9. Effect of Nose Radius on Cutting Speed.

TABLE 5

Job Description of a Turning Operation

Part: Variable recoil cylinder
Material: Steel tube 4140
Dimensions: 47.5" long, 8.5" dia., depth of cut 1/8"
Job order #: 0016011
Part #: 10895646
Cutting tool: Titanum coated carbide insert, multi-edged
Tool cost/edge: $.42
Machine tool specifications: Monarch stepped lathe
50 HP. RIA ID #30303
Available speeds (in rpm): 84, 95, 110, 126, 145, 166, 192, 220, 255, 290, 330, 380, 435
Available feeds (in ipr): .0032, .0035, .0037, .0038, .0042, .0047, .0013, .0060, .0065, .0070, .0073, .0076, .0084, .0093, .0105, .0120, .0129, .0140, .0146, .0153, .0168, .0187, .0210, .0240, .0259, .0293, .0306, .0337, .0374, .0421, .0451, .0518, .0561, .0585, .0612, .0673, .0748, .0841, .0962, .1036, .1122, .1171, .1224, .1346, .1496, .1683.
Labor and overhead rate: $18/hr.

TABLE 6

Data Summary of Ramberg Experiment [8]

Speed (RPM)	Feed (ipr)	No. of Parts	No. of Edges	Production Time	CU $/Part
192	0.0168	14	17	434	9.51
192	0.0187	18	18	410	7.28
192	0.0210	14	18	377	8.63
220	0.0168	13	23	396	9.90
220	0.0187	15	15	393	8.28
220	0.0210	20	44	440	7.52
255	0.0168	10	17	217	7.22
255	0.0187	11	29	267	8.39
255	0.0210	14	31	357	8.58

However, when one examines this data in detail it becomes apparent that the above results are very misleading due to a lack of control on the shop floor of other factors such as the handling time which varied from 9 minutes to 15.8 minutes per part.

The reason the 255 rpm and 0.0168 ipr feed combination gave the lowest CU was simply due to the operator loading and unloading the 10 pieces with an average handling time of 8.9 minutes per part. This value was calculated by assuming a tool indexing time of 1 minute. However, if the operator has loaded the machine at the same rate (8.9 minutes per part) when the conditions were set at 255 rpm and 0.0210 ipr, then the CU value would have been 6.57 $/part, or 10% cheaper.

Even this latter combination is not the optimum. Furthermore, it is practically impossible to find the optimum combination from such a trial and error method because of the operator variability from day to day as well as the work material variability from batch to batch. Also, it should be noted that nothing is said in regard to the tool shape which has a very important effect on tool life. In order to determine the optimum combination of speed and feed it is necessary to use a more analytical approach. The Fundamental Machinability Equation presented in section 2.2 of this report makes it possible to more reliably determine the optimum conditions, as explained below.

The rate of metal removal Q (cubic inches per minute) is approximately related to the conditions by the equation

$$Q = 12vfd$$

where v is the cutting speed in fpm, f is the feed and d is the depth of cut.

The Fundamental Machinability Equation can be rewritten as

$$v = Kf^{-0.67}d^{-0.33}$$

when the work material constant B and the tool constant A are combined into one constant K. This can be done when we want to examine the effect of feed and speed on productivity when keeping everything else constant. The exponents -0.67 and -0.33 are valid for cuts of approximately 1/8" depth and 0.02 ipr feed [6].

Because the feed exponent is less than 1.0, it is beneficial to always cut with as large a feed as is possible consistent with surface finish requirements and workpiece rigidity. This can be illustrated with a specific example.

Consider first the conditions of 0.125" depth and 0.010 ipr feed. The cutting speed is calculated as

$$v_1 = K(0.010)^{-0.67}(0.125)^{-0.33} = 43.45K$$

The resulting rate of metal removal is

$$Q_1 = 12 \times 43.45K \times .01 \times .125 = 0.65K \text{ cu in/min.}$$

Now if the feed were doubled to 0.020 ipr, the resulting cutting speed would be

$$v_2 = K(0.02)^{-0.67}(0.125)^{-0.33} = 27.31K$$

and the resulting rate of metal removal is

$$Q_2 = 12 \times 27.31K \times .02 \times .125 = 0.82K \text{ cu in/min.}$$

Thus it is apparent that doubling the feed increases the rate of metal removal by 0.17 cu in/min or 26%. This is due to the fact that since the feed exponent is less than 1.0, any per cent increase in feed does not require the same decrease in speed to achieve the same tool life. In the above example, doubling the feed from 0.010 ipr to 0.020 ipr required that the speed be reduced from 43.45K to 27.31K which is only a 37% reduction.

To illustrate the use of the HP 67 computer programs provided in section 4 of this report, the following example will be discussed. The hardness of the 4140 steel part is assumed to be 290 Brinell. The cutting is done with a C-7 grade of carbide having a 1/16" nose radius, 15° side cutting edge angle, 5° side rake and a 0° back rake angle. A 1/8" depth of cut on the 8.5" diameter bar is taken and a tool life range of 3 minutes to 15 minutes is satisfactory, based on the Ramberg report. Calculations will be based on a standard working day of 400 minutes, a 1 minute tool indexing time and 11 minute handling time.

If the above data are entered into the B1 series computer program, the results shown in Table 7 can be calculated as follows. First, by trial and error solution the tool life that results from a cutting speed of either 255 or 220 rpm must be determined. Then the cutting time can be calculated by dividing the length (47.5") by the product of the speed and the feed. That is, the time to cut $t_c = L/fN$. These two speeds were selected because they are the ones that are available on the actual production lathe.

The results shown in Table 7 indicate that if a speed of 255 rpm is used then the best feed is 0.0210 ipr based upon the lowest unit cost. This combination results in a total unit cost of $6.79. Feeds larger than 0.021 ipr result

in a higher tool cost that offsets the reduction in cutting time. However, if the maximum production rate is the basis of selecting the best feed, then the larger feed of 0.0259 ipr is better.

TABLE 7

Unit Costs Based on the Machinability Equation

Speed RPM	Feed ipr	Tool Life	Cutting Time	Tool Change Time	Handling Time	Total Time	Cost Labor	Cost Tool	Cost Total
255	.0168	15	11.09	0.74	11	22.83	6.85	.31	7.16
255	.0210	7.8	8.87	1.15	11	21.02	6.31	.48	6.79
255	.0259	3.8	7.19	1.89	11	20.08	6.02	.79	6.81
220	.0337	3.4	6.40	1.89	11	19.29	5.79	.79	6.58

The reason that the optimum feed in Table 7 is different from the optimum feed in Table 6 of the Ramberg [8] report is that the handling time of the Ramberg report was not maintained as a constant for all of the cutting conditions. For this reason, the data in Table 7 is more reliable for selecting the optimum feed for average day to day operating conditions on the shop floor.

The last line in Table 7 verifies the analysis made above in the discussion of the two equations:

$$Q = 12vfd$$

and

$$v = Kf^{-0.67}d^{-0.33}$$

It was demonstrated that best efficiency of metal removal is always obtained when as large a feed as possible is used providing that the speed that results in the optimum tool life is used.

Thus we see that when the speed is reduced to 220 rpm from 255 rpm and the feed increased to 0.0337, both the machining time and the unit cost are lower than those obtained for the smaller feeds.

In summary, the rules for selecting the optimum cutting conditions in the proper sequence are:

1. Select the best tool and shape.
2. Take as deep a cut as required. That is, one deep cut is better than 2 light ones.
3. Use as large a feed as is possible consistent with surface finish and rigidity.
4. Select the cutting speed that results in the optimum tool life by means of the computer programs given in section 4.

4. COMPUTER PROGRAMS

Three types of programs are presented in this report. The first two are programs to calculate the cutting speed for a given tool life. The first is a convenient program for a hand held HP 67 calculator that can be taken right out onto the shop floor. The second program utilizes the Fortran language. The third program relates the surface finish to the cutting conditions.

4.1 Cutting speed-tool life programs

4.1.1 HP 67 programs. Three different types of programs are included here. Series A is for HSS tools, Series B is for carbide tools and Series C is for carbide tools when either one of four standard tool holders are used. A separate program or card is used for the 4140 steel at 290 Brinell hardness level and another card for the steel at a hardness level of 200 Brinell.

4.1.1.1 Preliminary instructions. These preliminary instructions apply to all of the HP 67 programs. They give the general instructions necessary to activate the calculator and to record a program.

1. Turn the calculator ON-OFF switch to ON.
2. Set the PRGM-RUN switch to RUN.
3. Gently insert either end (printed side up) of the desired program card into the calculator reader slot. This is the lower slot on the right hand side of the calculator.

When the card is part way in, a motor engages and passes it out the opposite side. The card whould move freely and should never have to be forced.

The display will show "Error" if the card reads improperly. In this case, press CLX and reinsert the same end of the card as before.

The calculator will display "Crd" if the calculator wants to read the other side of your program card. In this case insert the opposite end of the card (face up) into the reader slot.

When the motor stops remove the program card from the end of the reader slot and insert it (face up) into the window slot which is located just above alphabetical keys A-E and just below the ON-OFF switch.

This program will remain stored until another program is loaded or the calculator is turned off.

If you still have any trouble loading your program refer to the calculator instruction book.

4.1.1.2 Series A and B programs. The following instructions apply to the programs or cards identified as A-1, A-2, B-1 or B-2. The programs A-1 and B-1 are to be used with 4140 steel at a hardness level of 290 Brinell. The A-2 and B-2 programs are for the softer steel having a hardness of 200 Brinell.

The A series are to be used with high speed steel tools, and the B series are for tungsten carbide tools. Both programs give the appropriate cutting speed when a copious supply of coolant is used. If cutting is done dry, then the speed must be reduced slightly.

1. If unfamiliar with loading a program into a HP calculator refer to the "Preliminary Instructions" which are located in paragraph 4.1.1.1.
2. Select the appropriate program card, program A for the use of high speed steel tools, and program B for the use of tungsten carbide tools.
3. Load the program into the calculator as instructed in the "Preliminary Instructions".
4. The program is now ready for use in the calculator. The data (machining variables) need to be inserted into the calculator nest. This is done in the following fashion:

   a. Insert the desired numerical value into the calculator by pressing in sequence the proper numerical keys.
      i.e.: For a feed of .008 ipr punch in order the keys .,0,0,8 (decimal point-zero-zero-eight).
      If you should make a mistake in punching in the number, press CLX (clear entry) and re-punch the correct number into the calculator.

b. After having successfully inserted the desired number press the STO key, this will tell the calculator to store (in memory) the number you punched into the display.

c. Press the appropriate key designated, to tell the calculator where to store your number.
   i.e.: If the feed .008 ipr is to be stored in memory one then press key 1.

5. The data should be inserted now using steps 4a-4c.

4A Step	4B key	4C key
Feed (inches per revolution)	STO	1
Depth of Cut (inches)	STO	2
Tool Life (min.)	STO	3
Side Cutting Edge Angle (degrees)	STO	4
Side Rake (degrees)	STO	5
Back Rake (degrees)	STO	6
Nose Radius (inches)	STO	7
O.D. of Cut Material (inches)	STO	8

6. The data is now inserted into the calculator's memroy and the program is ready to run. To run program A (HSS tool) press key A for grade T-1 or key B for grade T-15 tool material.

   Be sure to have a pencil and paper ready, the computed results will only be displayed for 5 seconds each. If you should miss one of the results then press the appropriate run key (A or B) again and the calculator will recalculate and display the results again. The data will be displayed in the following order:

   a. Vx Typical Cutting Velocity in feet per minute.
   b. Nx Typical Cutting Speed in rpm.

   If program B (tungsten carbide cutting tool) is to be run, then press key A when using a grade C-5 carbide tool, or press key B when using a grade C-7 carbide tool to run the program. Be sure to have pencil and paper ready, the computed results will only be displayed for 5 seconds each. If you should miss one of the results, then press the appropriate run key (A or B) again and the results will be displayed again. The data will be displayed in the the following order, with a 5 second pause between the first value and the second:

a. Vx Typical Cutting Velocity in feet per minute.
b. Nx Typical Cutting Speed in rpm.

7. The program and data will remain in the calculator until it is altered. This occurs when the calculator is turned off, or a new program is loaded into the calculator, or new data is entered into the memory (in this case only the data is altered and not the program). If you wish to run the same program again but wish to change some or all the data, then follow step 5 again skipping the values (machining variables) you wish to remain the same (they are still stored in the memory).

   The following examples will illustrate this procedure.

   a. Suppose that the feed is to be changed while all the other machining variable from the first run are held constant. Since all the old machining variables are still in the memory only the feed needs to be changed. This is done by punching in the new desired feed, then pressing the STO key then pressing key 1 (simply steps 4a-4c for only the feed).
   b. Suppose that in addition to changing the feed the nose radius is to be changed also. After changing the feed as done above, steps 4a-4c should be followed again for the nose radius. Punch in the desired new value for the nose radius, press the STO key, then press the number 7 numerical key. The calculator now has the new values for feed and nose radius and is ready to run as explained in step 6.

4.1.1.3 Series C programs. This series of programs is to be used whenever the carbide inserts are mounted in any one of the four standard tool holders listed below:

TH #1: SC = 0°, SR = -5°, BR = -5°
TH #2: SC = 15°, SR = -5°, BR = -5°
TH #3: SC = 15°, SR = 5°, BR = 0°
TH #4: SC = 0°, SR = 5°, BR = 0°

1. If unfamiliar with loading a program into a HP calculator refer to the "Preliminary Instructions" which are located in paragraph 4.1.1.1.
2. Load the program into the calculator as instructed by the "Preliminary Instructions".
3. The program is now ready for use in the calculator. The data (machining variables) needs to be inserted into the calculator next, this is to be done in the following fashion:

a. Insert the desired numerical value into the calculator by presenting in sequence the proper numerical keys.

   i.e.: For a feed of .008 ipr punch in order the keys .,0,0,8 (decimal point-zero-zero-eight).

   If you should make a mistake in punching in your number press CLX (clear entry) and re-punch the correct number into the calculator.

b. After having successfully inserted the desired number press the STO key, this will tell the calculator to store (in memory) the number you punched into the display.

c. Press the appropriate key designated, to tell the calculator where to store your number.

   i.e.: If the feed .008 ipr is to be stored in memory one then press key 1.

4. The data for the following variables should now be inserted using steps 3a-3c.

Steps

4A	4B	4C
Feed (inches per revolution)	STO	1
Depth of Cut (inches)	STO	2
Tool Life (min.)	STO	3
Nose Radius (inches)	STO	4
O.D. of Cut Material (inches)	STO	5

Press fA for C5 grade or fB for C7 grade.

5. The data is now inserted into the calculator's memory and the program is ready to run. In order to run the program now press key A, B, C, or D depending on which tool holder geometry will be used.

	To Run Press
TH #1: SC = 0°, SR = -5°, BR = -5°	A
TH #2: SC = 15°, SR = -5°, BR = -5°	B
TH #3: SC = 15°, SR = 5°, BR = 0°	C
TH #4: SC = 5°, SR = 5°, BR = 0°	D

where: SC = Side Cutting Edge Angle
SR = Side Rake Angle
BR = Back Rake Angle

Be sure to have a pencil and paper ready, the computed results will only be displayed for 5 seconds each. If you should miss one of the results then press the appropriate key again (A or B or C or D) and the calculator will recalculate and display the results again. The data will be displayed in the following order:

a. Vx Typical Cutting Velocity (fpm)
b. Nx Typical Cutting Speed (RPM)

6. The program and data will remain in the calculator until it is altered. This occurs when the calculator is turned off or a new program is loaded into the calculator or new data is entered into the memory (in this case only the data is altered and not the program). If you wish to run the same program again but wish to change some or all the data then follow step 5 again skipping the values (machining variables) you wish to remain the same (they are still stored in the memory).

The following examples will illustrate this procedure.

a. Suppose that the feed is to be changed while all the other machining variables from the first run are held constant. Since all the old machining variables are still in the memory only the feed needs to be changed. This is done by punching in the new desired feed, then pressing the STO key, then pressing key 1 (simply steps 3a-3c for only the feed).
b. Suppose that in addition to changing the feed the nose radius is to be changed also. After changing the feed as done above, steps 3a-3c should be followed again for the nose radius. Punch in the desired new value for the nose radius, press the STO key, then press the number 4 numerical key. The calculator now has the new values for feed and nose radius and is ready to run as explained in step 5.

4.1.1.4 HP 67 program preparation. Tables 8 through 13 give the sequence of key strokes that must be used to "write" a program or to prepare a new card for any of the series A, B, or C programs. To write a program the calculator W/PRGM-RUN switch must be set to the W/RPGM position and the OFF-ON switch turned to ON. Then the appropriate keys must be depressed in the proper sequence.

TABLE 8

PROGRAMMING STEPS FOR SERIES A-1 PROGRAM

001	*LBLE	051	TAN^{-1}	101	×	151	RCL2
002	2	052	RCLB	102	−	152	÷
003	5	053	÷	103	.	153	.
004	6	054	STOI	104	2	154	0
005	STOA	055	.	105	RCLA	155	5
006	.	056	2	106	.	156	CHS
007	0	057	CHS	107	0	157	Y^x
008	7	058	RCLI	108	0	158	×
009	2	059	X≤Y?	109	0	159	STOC
010	STOE	060	GTO1	110	3	160	RCL1
011	.	061	1	111	3	161	RCLD
012	0	062	RCLI	112	×	162	+
013	0	063	X≤Y?	113	−	163	RCLC
014	1	064	GTO2	114	RCLI	164	Y^x
015	8	065	4	115	×	165	RCL2
016	STOD	066	RCLI	116	−	166	RCLD
017	2	067	X≤Y?	117	*LBL4	167	+
018	1	068	GTO3	118	ST×0	168	1
019	STOE	069	1	119	RCL2	169	RCLC
020	RTN	070	GTO4	120	RCL7	170	−
021	*LBLA	071	*LBL1	121	1	171	Y^x
022	GSBE	072	.	122	RCL4	172	×
023	3	073	9	123	SIN	173	RCLE
024	[illegible]	074	GTO4	124	−	174	X⇄Y
025	GTOE	075	*LBL2	125	×	175	÷
026	*LBLB	076	.	126	−	176	RCL8
027	GSBE	077	6	127	RCL4	177	×
028	3	078	RCLA	128	COS	178	DSP0
029	3	079	.	129	÷	179	RND
030	*LBLE	080	0	130	RCL7	180	PRTX
031	RCL3	081	0	131	1	181	1
032	.	082	1	132	.	182	2
033	0	083	×	133	5	183	×
034	5	084	−	134	7	184	RCL8
035	5	085	RCLI	135	1	185	Pi
036	CHS	086	×	136	RCL4	186	×
037	Y^x	087	1	137	D→R	187	÷
038	[illegible]	088	+	138	−	188	RND
039	STO8	089	GTO4	139	×	189	PRTX
040	RCL5	090	*LBL3	140	+	190	DSP5
041	TAN	091	1	141	RCL2	191	RTN
042	RCL4	092	.	142	÷	192	R/S
043	COS	093	8	143	.		
044	[illegible]	094	RCLA	144	6		
045	RCL6	095	.	145	7		
046	TAN	096	0	146	Y^x		
047	RCL4	097	0	147	ST×0		
048	SIN	098	1	148	.		
049	×	099	3	149	6		
050	+	100	3	150	RCL1		

TABLE 9

PROGRAMMING STEPS FOR SERIES A-2 PROGRAM

001	*LBLE	051	TAN⁻¹	101	x	151	RCL2
002	1	052	RCLE	102	-	152	÷
003	5	053	÷	103	.	153	.
004	6	054	STOI	104	2	154	0
005	STOA	055	.	105	RCLA	155	5
006	.	056	2	106	.	156	CHS
007	1	057	CHS	107	0	157	Y^x
008	2	058	RCLI	108	0	158	x
009	5	059	X≤Y?	109	0	159	STOC
010	STOB	060	GTO1	110	3	160	RCL1
011	.	061	1	111	3	161	RCLD
012	0	062	RCLI	112	x	162	+
013	0	063	X≤Y?	113	-	163	RCLC
014	2	064	GTO2	114	RCLI	164	Y^x
015	3	065	4	115	x	165	RCL2
016	STOC	066	RCLI	116	-	166	RCLD
017	3	067	X≤Y?	117	*LBL4	167	+
018	1	068	GTO3	118	ST×0	168	1
019	STOD	069	1	119	RCL2	169	RCLC
020	RTN	070	GTO4	120	RCL7	170	-
021	*LBLA	071	*LBL1	121	1	171	Y^x
022	GSBE	072	.	122	RCL4	172	x
023	3	073	9	123	SIN	173	RCLE
024	0	074	GTO4	124	-	174	X⇄Y
025	GTO5	075	*LBL2	125	x	175	÷
026	*LBLB	076	.	126	-	176	RCL0
027	GSBE	077	6	127	RCL4	177	x
028	3	078	RCLA	128	COS	178	DSP0
029	1	079	.	129	÷	179	RND
030	*LBL5	080	0	130	RCL7	180	PRTX
031	RCL3	081	0	131	1	181	1
032	.	082	1	132	.	182	2
033	0	083	x	133	5	183	x
034	6	084	-	134	7	184	RCLE
035	5	085	RCLI	135	1	185	Pi
036	CHS	086	x	136	RCL4	186	x
037	Y^x	087	1	137	D→R	187	÷
038	x	088	+	138	-	188	RND
039	STO0	089	GTO4	139	x	189	PRTX
040	RCL5	090	*LBL3	140	+	190	DSP5
041	TAN	091	1	141	RCL2	191	RTN
042	RCL4	092	.	142	÷	192	R/S
043	COS	093	8	143	.		
044	x	094	RCLA	144	6		
045	RCLE	095	.	145	7		
046	TAN	096	0	146	Y^x		
047	RCL4	097	0	147	ST×0		
048	SIN	098	1	148	.		
049	x	099	3	149	6		
050	+	100	3	150	RCL1		

TABLE 10

PROGRAMMING STEPS FOR SERIES B-1 PROGRAM

001	*LBLE	051	TAN	101	1	151	RCL2	201	Pi
002	1	052	RCL4	102	.	152	÷	202	×
003	3	053	COS	103	8	153	4	203	÷
004	0	054	×	104	RCLA	154	.	204	RND
005	STO1	055	RCL6	105	.	155	3	205	PRTX
006	.	056	TAN	106	0	156	8	206	DSP5
007	0	057	RCL4	107	0	157	×	207	RTN
008	7	058	SIN	108	1	158	3	208	R/S
009	3	059	×	109	3	159	.		
010	STOE	060	+	110	3	160	3		
011	.	061	TAN^{-1}	111	×	161	6		
012	6	062	RCLB	112	-	162	-		
013	0	063	÷	113	.	163	STx0		
014	1	064	STOI	114	2	164	.		
015	6	065	.	115	RCLA	165	6		
016	STOD	066	2	116	.	166	RCL1		
017	3	067	CHS	117	0	167	RCL2		
018	1	068	RCLI	118	0	168	÷		
019	STOE	069	X≤Y?	119	0	169	.		
020	RTN	070	GTO1	120	3	170	0		
021	*LBLA	071	1	121	3	171	5		
022	GSBE	072	RCLI	122	×	172	CHS		
023	4	073	X≤Y?	123	-	173	Y^x		
024	GTO5	074	GTO2	124	RCLI	174	×		
025	*LBLB	075	4	125	×	175	STOC		
026	GSBE	076	RCLI	126	-	176	RCL1		
027	4	077	X≤Y?	127	*LBL4	177	RCLD		
028	.	078	GTO3	128	STx0	178	+		
029	5	079	1	129	RCL2	179	RCLC		
030	*LBLE	080	GTO4	130	RCL7	180	Y^x		
031	RCL3	081	*LBL1	131	1	181	RCL2		
032	.	082	.	132	RCL4	182	RCLD		
033	1	083	9	133	SIN	183	+		
034	4	084	GTO4	134	-	184	1		
035	CHS	085	*LBL2	135	×	185	RCLC		
036	Y^x	086	.	136	-	186	-		
037	×	087	6	137	RCL4	187	Y^x		
038	STOC	088	RCLA	138	COS	188	×		
039	3	089	.	139	÷	189	RCLE		
040	0	090	0	140	RCL7	190	X⇄Y		
041	RCL3	091	8	141	1	191	÷		
042	.	092	1	142	.	192	RCL0		
043	0	093	×	143	5	193	×		
044	6	094	-	144	7	194	DSP0		
045	5	095	RCLI	145	1	195	RND		
046	CHS	096	×	146	RCL4	196	PRTX		
047	Y^x	097	1	147	D→R	197	1		
048	×	098	+	148	-	198	2		
049	STx0	099	GTO4	149	×	199	×		
050	RCL5	100	*LBL3	150	+	200	RCL8		

TABLE 11

PROGRAMMING STEPS FOR SERIES B-2 PROGRAM

001	*LBLE	051	TAN	101	1	151	RCL2	201	Pi
002	1	052	RCL4	102	.	152	÷	202	×
003	5	053	COS	103	8	153	4	203	÷
004	6	054	×	104	RCLA	154	.	204	RND
005	STOA	055	RCL6	105	.	155	3	205	PRTX
006	.	056	TAN	106	0	156	9	206	DSP5
007	1	057	RCL4	107	0	157	×	207	RTN
008	2	058	SIN	108	1	158	2	208	R/S
009	5	059	×	109	3	159	.		
010	STOB	060	+	110	3	160	3		
011	.	061	TAN⁻¹	111	×	161	8		
012	0	062	RCLB	112	-	162	-		
013	0	063	÷	113	.	163	ST×0		
014	2	064	STOI	114	2	164	.		
015	3	065	.	115	RCLA	165	6		
016	STOD	066	2	116	.	166	RCL1		
017	3	067	CHS	117	0	167	RCL2		
018	1	068	RCLI	118	0	168	÷		
019	STOE	069	X≤Y?	119	0	169	.		
020	RTN	070	GTO1	120	3	170	0		
021	*LBLA	071	1	121	3	171	5		
022	GSBE	072	RCLI	122	×	172	CHS		
023	4	073	X≤Y?	123	-	173	Y^x		
024	STO5	074	GTO2	124	RCLI	174	×		
025	*LBL5	075	4	125	×	175	STOC		
026	GSBE	076	RCLI	126	-	176	RCL1		
027	4	077	X≤Y?	127	*LBL4	177	RCLD		
028	.	078	GTO3	128	ST×0	178	+		
029	5	079	1	129	RCL2	179	RCLC		
030	*LBL3	080	GTO4	130	RCL7	180	Y^x		
031	RCL3	081	*LBL1	131	1	181	RCL2		
032	.	082	.	132	RCL4	182	RCLD		
033	1	083	3	133	SIN	183	+		
034	4	084	GTO4	134	-	184	1		
035	CHS	085	*LBL2	135	×	185	RCLC		
036	Y^x	086	.	136	-	186	-		
037	÷	087	6	137	RCL4	187	Y^x		
038	STO0	088	RCLA	138	COS	188	×		
039	3	089	.	139	÷	189	RCLE		
040	0	090	0	140	RCL7	190	X⇄Y		
041	RCL3	091	0	141	1	191	÷		
042	.	092	1	142	.	192	RCL0		
043	0	093	×	143	5	193	×		
044	5	094	-	144	7	194	DSP0		
045	5	095	RCLI	145	1	195	RND		
046	CHS	096	×	146	RCL4	196	PRTX		
047	Y^x	097	1	147	D→R	197	1		
048	×	098	+	148	-	198	2		
049	ST×0	099	GTO4	149	×	199	×		
050	RCL5	100	*LBL3	150	÷	200	RCL8		

TABLE 12

PROGRAMMING STEPS FOR SERIES C-1 PROGRAM

001	*LBLb	051	*LBLD	101	.	151	1
002	4	052	0	102	0	152	2
003	.	053	STOA	103	0	153	×
004	5	054	1	104	1	154	RCL5
005	RCL3	055	.	105	8	155	PI
006	.	056	0	106	STOC	156	×
007	1	057	8	107	3	157	÷
008	4	058	3	108	0	158	RND
009	CHS	059	ST×0	109	RCL3	159	0
010	Y^x	060	*LBLE	110	.	160	STO0
011		061	RCL2	111	0	161	R↓
012	STO0	062	RCL4	112	6	162	DSP2
013	RTN	063	1	113	5	163	RCL9
014	*LBLa	064	RCLA	114	CHS	164	PRTX
015	4	065	SIN	115	Y^x	165	X≷Y
016	RCL3	066	−	116	×	166	PRTX
017	.	067	×	117	ST×0	167	RTN
018	1	068	−	118	.	168	R/S
019	4	069	RCLA	119	6		
020	CHS	070	COS	120	RCL1		
021	Y^x	071	÷	121	RCL2		
022	×	072	RCL4	122	÷		
023	STO0	073	1	123	.		
024	RTN	074	.	124	0		
025	*LBLA	075	5	125	5		
026	6	076	7	126	CHS		
027	STOA	077	1	127	Y^x		
028	.	078	RCLA	128	×		
029	9	079	D→R	129	STOD		
030	ST×0	080	−	130	RCL1		
031	GTOE	081	×	131	RCLC		
032	*LBLB	082	+	132	+		
033	1	083	RCL2	133	RCLD		
034	5	084	÷	134	Y^x		
035	STOA	085	4	135	RCL2		
036	.	086	.	136	RCLC		
037	9	087	3	137	+		
038	ST×0	088	6	138	1		
039	GTOE	089	×	139	RCLD		
040	*LBLC	090	2	140	−		
041	1	091	.	141	Y^x		
042	5	092	3	142	×		
043	STOA	093	8	143	RCL5		
044	1	094	−	144	X≷Y		
045	.	095	ST×0	145	÷		
046	0	096	.	146	RCL6		
047	6	097	0	147	×		
048	1	098	7	148	DSP6		
049	ST×0	099	2	149	RND		
050	GTOE	100	STOB	150	STO9		

TABLE 13

PROGRAMMING STEPS FOR SERIES C-2 PROGRAM

001	*LBLa	051	7	101	2	151	DSP0
002	4	052	STx0	102	5	152	RND
003	.	053	GTOE	103	STOE	153	STO9
004	5	054	*LBLD	104	.	154	1
005	RCL3	055	0	105	0	155	2
006	.	056	STOA	106	0	156	x
007	1	057	1	107	2	157	RCL5
008	4	058	.	108	3	158	Pi
009	CHS	059	0	109	STOC	159	x
010	Y^x	060	7	110	3	160	÷
011	x	061	3	111	0	161	RND
012	STO0	062	STx0	112	RCL3	162	0
013	RTN	063	*LBLE	113	.	163	STO0
014	*LBLb	064	RCL2	114	0	164	R↓
015	4	065	RCL4	115	6	165	DSP6
016	RCL3	066	1	116	5	166	RCL9
017	.	067	RCLA	117	CHS	167	PRTX
018	1	068	SIN	118	Y^x	168	X⇄Y
019	4	069	-	119	x	169	PRTX
020	CHS	070	x	120	STx0	170	RTN
021	Y^x	071	-	121	.	171	R/S
022	x	072	RCLA	122	6		
023	STO0	073	COS	123	RCL1		
024	RTN	074	÷	124	RCL2		
025	*LBLA	075	RCL4	125	÷		
026	0	076	1	126	.		
027	STOA	077	.	127	9		
028	.	078	5	128	5		
029	9	079	7	129	CHS		
030	2	080	1	130	Y^x		
031	7	081	RCLA	131	x		
032	STx0	082	D→R	132	STOD		
033	GTOE	083	-	133	RCL1		
034	*LBLB	084	x	134	RCLC		
035	1	085	+	135	+		
036	5	086	RCL2	136	RCLD		
037	STOA	087	÷	137	Y^x		
038	.	088	4	138	RCL2		
039	9	089	.	139	RCLC		
040	1	090	3	140	+		
041	1	091	6	141	1		
042	STx0	092	x	142	RCLD		
043	GTOE	093	2	143	-		
044	*LBLC	094	.	144	Y^x		
045	1	095	3	145	x		
046	5	096	5	146	RCLE		
047	STOA	097	-	147	X⇄Y		
048	1	098	STx0	148	÷		
049	.	099	.	149	RCL0		
050	0	100	1	150	x		

To illustrate this operation, consider the series A-1 program in Table 8. The first line has the key strokes * LBL E indicated. To accomplish this the three keys f, LBL, and E must be depressed in that order. Note that whenever an * appears in front of LBL, it represents the gold key labeled f.

The second, third and fourth lines indicate that the number 250 is to be entered. (This is the Brinell hardness at 600°F of the 300 Brinell hardness 4140 steel.) The fifth line indicates that this value is to be stored in register A. This is done by depressing the STO key and then the A key. The remaining entries, through line 192, are made in similar fashion.

If it is desired to record this program on a magnetic card, the keys GTO,.(period),0,0,0 must be depressed. The key stroke sequence is GTO,.,0,0,0. Now a card can be run through the calculator to record the program on the card. In this case, both ends of the card must be run through the calculator since the program is too long to be recorded on 1 side only. If it is desired to now proceed with cutting speed calculations, the W/PRGM-RUN switch should be moved to the RUN position. Then the machining conditions should be stored in the appropriate registers according to the instructions given in paragraph 4.1.1.2.

The following explanations will help in understanding the program listed in Table 8. The material factor B for this steel is 0.072 and is entered on lines 6 through 9 of the program. The strain hardening factor y is 0.0018 and is entered in lines 11 through 15. The optimum effective rake angle is entered in lines 17 and 18. The tool life proportionality constant for T-1 HSS is 30 and is entered on lines 23 and 24. The value for T-15 HSS is 33 and is entered on lines 28 and 29. The tool life constant A_t is calculated and stored in D (see line 39).

The effective rake angle is calculated in lines 40 through 53 and the effective rake constant A_e is calculated in lines 55 through 118. The length of the cutting edge constant is determined in lines 119 through 147. The feed exponent a is calculated between lines 148 and 155. The size of cut constant q is determined in lines 156 through 172.

The cutting speed in feet per minute is calculated in lines 173 through 180 and is converted to RPM in lines 181 through 190. The last two lines are simply instructions for the calculator to return to the beginning of the program (line 000) so that new cutting conditions can be entered.

The A-2 program is identical to the A-1 just described, except that the hardness, the B value, and the y factor have

different numerical values. The B series programs are similar to the A series except for the tool material constant A_m. The C series programs are shorter than the A and B ones because the effective rake angle is a constant built into the program for the four standard tool holders.

To write a program for a different material simply requires that the properties of the new material be substituted for those of the original material. All of the necessary equations are presented in section 2 of this report.

4.1.2 Fortran program. A description of the Fortran program is given in Appendix A, including a copy of the complete program. In addition, a complete stack of computer cards for the main body of the program, cards for three runs (three separate sets of data), and a complete set of print-out sheets have been given to the sponsor of this project. Because of the size and bulk of the computer cards, and the fact that they are intended to be used in computations, they are not bound into the body of this report. Instead, they are presented as a separate package.

Cards number 1 through number 150 contain the main program. The data for any turning operation is entered on subsequent cards. For example, in the stack of cards included with this project, card number 151 which is identified with the code 001 in the upper left hand corner contains the input data for the first run. The input data must be punched onto the data card in the following sequence: tool life, Brinell hardness, side rake angle, nose radius, side cutting edge angle, depth of cut, feed, bar radius or wall thickness, thermal conductivity, per cent area reduction from a tensile test, strain strengthening exponent, back rake angle,.

It must be noted that commas must be included after each variable and at the end of the data. Thus the input data, with the proper program symbols looks like this: T, HB6, SR, R, SCE, D, F, H, ZK6, AR6, ZM, BR,

The input data on card 001 is displayed on the top of card number 152 which follows the card identified as 001 and also in Table A-5 of Appendix A. The conditions used for this run are: 60 minute tool life, 300 Brinell hardness (250 Brinell hardness at 600°F), nose radius of 0.047", 15° side cutting edge angle, 0.090" depth of cut, 14° side rake angle, 0.008 ipr feed, 2" radius bar size, thermal conductivity of 21.5 BTU/hr ft °F, 29.6% area reduction, strain strengthening exponent of 0.11, 8° back rake angle. The tool material is T-1 high speed steel with flood coolant.

The program is set up to print out the eight tool and environment constants A as well as the work material constant B and size of cut constant q. These are useful in many cases when it is desired to optimize the turning operation since they show the magnitude of each of the individual factors.

The bottom line of the program gives the recommended cutting speed in feet per minute. In this case it is 124 fpm. This compares very favorably with the experimental value which was found to be 120 fpm.

The input data for the second run is entered on the card identified as 002 and is displayed on the following card. Additional data can be entered on new cards and coded in sequence 003, 004, etc.

4.2 Surface finish programs. These surface finish programs are intended to assist the NC programmer in selecting the optimum cutting conditions that will give the machined surface a finish equal to that specified on the part drawing. The surface finish is measured across the feed marks and is expressed as RMS microinches (μ in).

4.2.1 HP 67 program. This program is much more practical for the NC programmer, or for any parts processor, than the more complete Fortran program that follows. The HP 67 program enables the user to predict the surface finish that will result from various cutting conditions. The same program can also be used to select the cutting conditions that will produce a specified surface finish. This program is based on the four equations listed below that were developed from experimental work done at The University of Michigan over the past 20 years as well as from some data given in Volume 3 of the ASM Handbook [8] and the Sandvik Tool Catalog E-8040B:2.

The factors that are included in these equations are the feed in ipr, the nose radius in inches, and the cutting speed in fpm. The equations are based on the concept of a theoretical surface finish derived in Appendix B. The theoretical surface finish (expressed as SFT) is the root mean square roughness measured across the feed marks when it is assumed that all lines in the direction of cutting are perfectly smooth and straight. It is the lowest value of surface finish that could ever be attained under ideal cutting conditions.

In the actual cutting condition, as the chip is formed ahead of the tool's cutting edge, the metal is sheared and the resulting machined surface is ragged or serrated. On a microscopic scale it resembles a freshly plowed field. The roughness of a turned surface decreases as the cutting speed

increases for all ductile metals. At the high speeds attainable with carbide tools, the actual surface finish (expressed as SFA) approaches the theoretical value.

The four equations are:

1. $SFT = 41{,}000\ f^2 R^{-1.04}$

2. $SFA = SFT(1 + 1.75\ e^{-V/150})$

3. $R = 26{,}500\ SFT^{-0.96} f^{1.92}$

4. $f = 0.0049\ SFT^{0.5} R^{0.52}$

The first equation makes it possible to calculate the theoretical surface finish from the feed f and the nose radius R. The cutting speed does not affect the theoretical surface finish.

The second equation permits the calculation of the actual surface finish as a function of the cutting speed being used--low speeds giving a rough surface and very high speeds creating surface finishes almost as smooth as the theoretical ones.

The third equation determines the nose radius that is needed to obtain a specified surface finish when the feed is selected first. Although the third and fourth equations have the theoretical surface finish in them, the equations are entered into the calculator programs in such a way that the actual surface finish can be entered and the calculator automatically makes the conversion.

The fourth equation is similar to the third one just described except that the output is now the maximum feed that can be used for a given nose radius, surface finish and speed.

The programming steps for the HP 67 surface finish program are listed in Table 14. The following examples will illustrate the use of this program. First, the program has to be entered into the calculator. (Two programmed magnetic cards are forwarded to the sponsor along with the stacks of Fortran cards in a separate package.) This can be done either by entering the keystrokes listed in Table 14 or by using one of the programmed cards.

The input data has to be stored into the calculator in the locations listed in Table 15.

TABLE 14

PROGRAMMING STEPS FOR THE SURFACE FINISH PROGRAM

001	*LBLA	051	GSBA	101	RCLA
002	4	052	RCLE	102	X=0?
003	1	053	X=0?	103	GSBA
004	EEX	054	÷	104	√X
005	3	055	1	105	RCLC
006	RCLD	056	5	106	X=0?
007	√X	057	0	107	÷
008	×	058	CHS	108	.
009	RCLC	059	÷	109	5
010	X=0?	060	e^x	110	2
011	GTOa	061	1	111	Y^x
012	1	062	.	112	×
013	.	063	7	113	4
014	0	064	5	114	9
015	4	065	×	115	EEX
016	CHS	066	1	116	CHS
017	Y^x	067	+	117	4
018	×	068	÷	118	×
019	X=0?	069	STO2	119	STO4
020	GTOa	070	DSP0	120	DSP4
021	STO1	071	RTN	121	RTN
022	DSP0	072	*LBLC	122	*LBLE
023	RTN	073	RCLA	123	RCLA
024	*LBLa	074	X=0?	124	X=0?
025	RCLB	075	GSBA	125	GSBA
026	X=0?	076	.	126	RCLB
027	÷	077	9	127	X⇄Y
028	RCLE	078	6	128	÷
029	X=0?	079	CHS	129	1
030	÷	080	Y^x	130	−
031	1	081	RCLD	131	1
032	5	082	X=0?	132	.
033	0	083	÷	133	7
034	CHS	084	1	134	5
035	÷	085	.	135	÷
036	e^x	086	9	136	LN
037	1	087	2	137	1
038	.	088	Y^x	138	5
039	7	089	×	139	0
040	5	090	2	140	CHS
041	×	091	6	141	×
042	1	092	.	142	STO5
043	+	093	5	143	DSP0
044	÷	094	EEX	144	RTN
045	STO1	095	3	145	R/S
046	DSP0	096	×		
047	RTN	097	STO3		
048	*LBLB	098	DSP3		
049	RCLA	099	RTN		
050	X=0?	100	*LBLD		

TABLE 15

STORAGE LOCATIONS FOR THE SURFACE FINISH PROGRAM

Input Data	Stored Location
SFT (theoretical surface finish)	A
SFA (actual surface finish)	B
R (nose radius)	C
f (feed)	D
v (cutting speed, fpm)	E

The first example will illustrate the method for determining the surface finish that can be expected for a set of cutting conditions. Assume the tool has a nose radius of 1/16", the feed is 0.015 ipr and the speed is 500 fpm. After the program has been entered, the radius is entered by pressing in sequence the keys . 0 6 2 STO C.

The feed is entered by pressing in sequence the keys . 0 1 5 STO D.

The cutting speed is entered by pressing the keys 5 0 0 STO E.

To obtain the actual surface finish, the B key is depressed and resulting answer 177 is displayed. If the A key is depressed instead, the theoretical surface finish is displayed as 166.

If an actual surface finish of 125 is required, either a larger nose radius must be used, or else a smaller feed must be selected. The second example will illustrate the former case, that is, what is the minimum value of nose radius that will give a 125 actual surface finish with a feed of 0.015 ipr. The surface finish is entered into the calculator by pressing in sequence the keys 1 2 5 STO B. The feed and speed are the same as in illustration 1, so they need not be changed now. (However, if the calculator were turned off, then the feed and speed would have to be entered again.) Since the nose radius to be calculated in this case, it is first necessary to take out the previously entered value of .062 in register C. This is done by pressing in sequence the keys 0 STO C. The answer is obtained by pressing the C key, and the minimum nose radius of 0.086" is displayed.

Example 3 will illustrate the manner of determining the maximum feed that could be used with a 1/16" nose radius and a 500 fpm velocity to obtain a 125 actual surface finish. In this case, the 125 SFA is stored in B, the 0.062 radius is

stored in C, and the 500 fpm is stored in E. When the D key is now pressed, the maximum feed of 0.0125 is displayed as the answer.

If insufficient data, or improper data, is given the calculator will display ERROR as the answer. For example, if a SFA of 125 is stored in B, a radius of 0.062 is stored in C, and then if the D key is pressed the calculator will display ERROR. In this case the cutting speed was not entered. If now the correct speed is stored in E, the calculator will display the maximum feed.

By means of this surface finish program, the NC programmer can soon learn that surface finishes of 63 RMS or less can be obtained only with very small feeds and high cutting speeds. Likewise, with large feeds and modest nose radius, finishes less than 250 RMS cannot be obtained.

4.2.2 The Fortran program. The programming steps for the fortran surface finish program are listed in Table 16. The program is based on the equations for calculating the theoretical surface finish as a function of the feed, nose radius, end cutting edge angle (EC), and the side cutting edge angle (SC).

The actual (real) machined surface finish is also a function of the cutting speed. In this program the actual surface finish is calculated from the theoretical surface finish by means of the graphical relationship given in Vol. 3 of the Metals Handbook [9]. By analyzing the graphical data it was found that the ratio of the actual surface finish (SFA) to the theoretical surface finish (SFT) could be accurately represented by the equation

$$SFA/SFT = 1 + 1.75\ e^{-v/150}$$

This equation is valid for ductile steel such as 4140. Similar equations can be developed for other metals such as cast iron and bronze.

Table 17 is a copy of a print-out sheet for a typical run of the computer program. In this turning operation the feed is 0.010 ipr, the nose radius is 0.030", the end cutting edge angle is 6°, and the side cutting edge angle is 15°. The surface finish for cutting speeds of 100 and 400 fpm are calculated. The results at the bottom of the table are: 126 RMS theoretical surface finish; 240 RMS for a velocity of 100 fpm; 142 RMS for a cutting speed of 400 fpm.

TABLE 16. Programming Steps for the Fortran Surface Finish Program

```
$FUN *FTN
C      THIS PROGRAM CALCULATES THE ROOT MEAN SQUARE  OF A SURFACE FINISH
       DIMENSION Y(20),X(20),H(20)
       DOUBLE PRECISION Y1,Y2,Y3,Y4,Y,RMS,RMS1,RMS2,RMS3,RMS4,RMS5
       DOUBLE PRECISION F,R,EC,SC,A1,A2,A3,A4,A,XA,XB,XC,BT,YC,V1,V2
90     READ 2,F,R,EC,SC,V1,V2
2      FORMAT(6F10.0)
       IF(F.EQ.0.00) GO TO 999
       PRINT 3, F
3      FORMAT('1 THE FEED......................F=',F8.3,'INCHES PER REV.'
      1//)
       PRINT 4,R
4      FORMAT('THE TOOL'S NOSE RADIUS.........R=',F8.3,'INCHES'//)
       PRINT 5, EC
5      FORMAT ('THE END CUTTING EDGE ANGLE...EC=',F8.3,' DEGREES'//)
       PRINT 6, SC
6      FORMAT('THE SIDE CUTTING EDGE ANGLE...SC=',F8.3,'DEGREES'//)
       PRINT 12,V1,V2
12     FORMAT('CUTTING VELOCITIES.........V1,V2=',F8.3,F8.3,'FPM'//)
       SC=SC*0.0174533
       EC=EC*0.0174533
       F=(10**6)*F
       R=(10**6)*R
       IF(F.GT.8*R)GO TO 80
       IF (F.LT.2.*R*DSIN(EC))GO TO 98
       GO TO 50
80     PRINT 81
81     FORMAT('SINCE FEED IS GREATER THAN 8*NOSE RADIUS,NO RMS RESULTS')
       GO TO 90
C      THE FOLLOWING CALCULATIONS ARE VALID ONLY FOR FEED<2*R*SIN(EC)
C      AND EC=6DEGREES :SC=15 DEGREES
98     XC=F/2.D0
       YC=DSQRT(R**2-F**2/4.D0)
       BT=DARCOS(YC/R)
       A1=R**2*(DSIN(BT)-(DSIN(2*BT))/4-BT/2)
       Y=(R*DSIN(BT))**3/6/A1
       PRINT 1
1      FORMAT('THESE ARE INTERMEDIATE CALCULATIONS$$$$$$$$$$$$$$$$$$$$$')
       PRINT 27,XC,YC,Y,BT,A1
27     FORMAT('XC=',F15.3,'YC=',F15.3,'Y=',F15.3, BT=',F15.9,'A1=',F15.3)
       RMS=0
       DO 23 I=1,11
       X(I)=(I-1)*XC/10
       H(I)=DABS(Y-DSQRT(R**2-(X(I))**2.D0))
       PRINT 28,I,X(I),I,H(I)
28     FORMAT('X(',I2,')=',F15.3,'H(',I2,')=',F15.3)
       RMS=RMS+(H(I))**2
23     CONTINUE
       RMS=DSQRT(RMS/11)
       PRINT 34
34     FORMAT('-RESULTS$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$')
       PRINT 24,RMS
24     FORMAT('THE THEORETICAL ROOT MEAN SQUARE IS: RMS=',F8.3)
       RMS4=RMS*(1.+1.75*DEXP(V1/(-150.)))
       RMS5=RMS*(1.+1.75*DEXP(V2/(-150.)))
       PRINT 25,V1,RMS4
25     FORMAT('RMS FOR V=',F8.3,'FPM IS :RMS=',F8.3)
       PRINT 26,V2,RMS5
26     FORMAT('RMS FOR V=',F8.3,'FPM IS :RMS=',F8.3)
       GO TO 90
```

Table 16 continued

```
C     THE FOLLOWING CALCULATIONS ARE VALID ONLY FOR FEED<8*R
C     AND EC=60DEGREES  ;SC=15 DEGREES;ALSO FEED>2*R*SIN(EC)
50    XA=0
      PRINT 11
11    FORMAT('THESE ARE INTERMEDIATE CALCULATIONS$$$$$$$$$$$$$$$$$$$$')
      XB=R*DSIN(EC)
      B=(DTAN(EC))*(F*DCOS(EC)+R*DTAN(EC)*DSIN(EC))+F
      XC=(B-DSQRT(B**2-((DTAN(EC))**2+1)*((F*DCOS(EC)+F*DTAN(EC)*
     1DSIN(EC))**2+F**2-R**2)))/((DTAN(EC))**2+1)
      PRINT 59,XC,XB
59    FORMAT('XC=',F15.3,'XB=',F15.3)
      YC=-(DTAN(EC))*XC+R*DCOS(EC)+R*DTAN(EC)*DSIN(EC)
      PRINT 60,YC
60    FORMAT('YC=',F15.3)
      BT=DARCOS(YC/R)
      PRINT 9,BT
9     FORMAT('BT=',F15.3)
      A1=R**2*(DSIN(EC)-(DSIN(2*EC))/4-EC/2)
      Y1=(R*DSIN(EC))**3/6/A1
      A3=R**2*(DSIN(BT)-(DSIN(2*BT))/4-BT/2)
      Y3=(R*DSIN(BT))**3/6/A3
      A2=R*(1-DCOS(EC))*(XC-R*DSIN(EC))
      Y2=R*(1+DCOS(EC))/2
      A4=(XC-R*DSIN(EC))*(R*DCOS(EC)-YC)/2
      Y4=(YC+2*R*DCOS(EC))/3
      PRINT 7,A1,A2,A3,A4
7     FORMAT('A1=',F15.3,'***A2=',F15.3,'***A3=',F15.3,'***A4=',F15.3)
      PRINT 8,Y1,Y2,Y3,Y4
8     FORMAT('Y1=',F15.3,'***Y2=',F15.3,'***Y3=',F15.3,'***Y4=',F15.3)
      A=A1+A2+A3+A4
      PRINT 61,A
61    FORMAT('A=',F15.3)
      Y=(A1*Y1+A2*Y2+A3*Y3+A4*Y4)/A
      PRINT 62,Y
62    FORMAT('Y=',F15.3)
      RMS1=0
      DO 70 I=1,11
      X(I)=(I-1)*XB/10
      V(I)=DABS(Y-DSQRT(R**2-(X(I))**2))
      PRINT 71,I,X(I),I,V(I)
71    FORMAT('X(',I2,')=',F15.3,'    V(',I2,')=',F15.3)
      RMS1=RMS1+(V(I))**2
70    CONTINUE
      I1=I
      RMS2=0
      DO 72 I=1,10
      X(I)=XB+I*(XC-XB)/10
      V(I)=DABS(Y+DTAN(EC)*X(I)-R*DCOS(EC)-R*DTAN(EC)*DSIN(EC))
      PRINT 73,I,X(I),I,V(I)
73    FORMAT('X(',I2,')=',F15.3,'    V(',I2,')=',F15.3)
      RMS2=RMS2+(V(I))**2
72    CONTINUE
      I2=I
      RMS3=0
      DO 74 I=1,10
      X(I)=I*(F-XC)/10+XC
      V(I)=DABS(Y-DSQRT(R**2-(DABS(X(I )-F))**2.D0))
      PRINT 75,I,X(I),I,V(I)
75    FORMAT('X(',I2,')=',F15.3,'    V(',I2,')=',F15.3)
      RMS3=RMS3+(V(I))**2
```

Table 16 continued

```
74    CONTINUE
      I3=I
      N=I1+I2+I3
      RMS=DSQRT((RMS1+RMS2+RMS3)/N)
      PRINT 33
33    FORMAT('-RESULT$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$')
      PRINT 35,RMS
35    FORMAT('THE THEORETICAL ROOT MEAN SQUARE IS: RMS=',F8.3)
      RMS4=RMS*(1.+1.75*DEXP(V1/(-150.)))
      RMS5=RMS*(1.+1.75*DEXP(V2/(-150.)))
      PRINT 63,V1,RMS4
63    FORMAT('RMS FOR V=',F8.3,'PPM IS :RMS=',F8.3)
      PRINT 64,V2,RMS5
64    FORMAI('RMS FOR V=',F8.3,'PPM IS :RMS=',F8.3)
      GO TO 90
999   STOP
      END
$END FILE
```

TABLE 17. Print-Out of a Typical Computer Run

```
THE FEED.......................F= 0.010INCHES PER REV.
THE TOOL S NOSE RADIUS.........R= 0.030INCHES
THE END CUTTING EDGE ANGLE....EC= 6.000 DEGREES
THE SIDE CUTTING EDGE ANGLE...SC= 15.000DEGREES
CUTTING VELOCITIES.........V1,V2= 100.000 400.000FPM
THESE ARE INTERMEDIATE CALCULATIONS$$$$$$$$$$$$$$$$$$$$
XC=        5219.472XB=        3135.855
YC=       29616.660
BT=           0.160
A1=      171506.863***A2=      342428.373***A3=       609286.871**
Y1=       29950.720***Y2=       29917.828***Y3=        29885.125**
A=      1351465.087
Y=        29381.065
X( 1)=           0.0      V( 1)=          118.935
X( 2)=         313.585    V( 2)=          117.296
X( 3)=         627.171    V( 3)=          112.378
X( 4)=         940.756    V( 4)=          104.181
X( 5)=        1254.342    V( 5)=           92.701
X( 6)=        1567.927    V( 6)=           77.934
X( 7)=        1881.513    V( 7)=           59.875
X( 8)=        2195.098    V( 8)=           38.519
X( 9)=        2508.684    V( 9)=           13.859
X(10)=        2322.269    V(10)=           14.114
X(11)=        3135.855    V(11)=           45.408
X( 1)=        3344.217    V( 1)=           67.308
X( 2)=        3552.578    V( 2)=           89.208
X( 3)=        3760.940    V( 3)=          111.107
X( 4)=        3969.302    V( 4)=          133.007
X( 5)=        4177.660    V( 5)=          154.907
X( 6)=        4386.023    V( 6)=          176.806
X( 7)=        4594.387    V( 7)=          198.706
X( 8)=        4802.746    V( 8)=          220.606
X( 9)=        5011.109    V( 9)=          242.506
X(10)=        5219.469    V(10)=          264.405
X( 1)=        5597.523    V( 1)=          191.190
X( 2)=        6175.574    V( 2)=          125.834
X( 3)=        6653.629    V( 3)=           68.286
X( 4)=        7131.680    V( 4)=           18.501
X( 5)=        7609.734    V( 5)=           23.560
X( 6)=        8087.785    V( 6)=           57.930
X( 7)=        8565.840    V( 7)=           84.635
X( 8)=        9043.891    V( 8)=          103.695
X( 9)=        9521.945    V( 9)=          115.126
X(10)=       10000.000    V(10)=          118.935

RESULT$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
THE THEORETICAL ROOT MEAN SQUARE IS: RMS= 126.344
RMS FOR V= 100.000FPM IS :RMS= 239.861
RMS FOR V= 400.000FPM IS :RMS= 141.707
```

4.3 Horsepower requirements. Before the optimum cutting conditions that are calculated by means of the cutting speed-tool life programs listed in section 4.1 are implemented, it must first be determined if the machine tool has sufficient power to actually cut at the specified conditions. The calculator program listed here will enable the parts processor or NC programmer to determine whether the machine tool has sufficient power, and if not, it will enable him to determine the maximum feed or speed that can be used. The program is based on the following two equations which were calculated from the analytical cutting force equation given in Datsko [3].

1. $HP = 4.03 \; f \times d \times OD \times N$ for 290 H_B

2. $HP = 2.78 \; f \times d \times OD \times N$ for 200 H_B

In both equations, f is the feed in ipr, d is the depth of cut in inches, OD is outside diameter in inches, and N is the spindle RPM. These equations can be used for carbide and ceramic tools. The horsepower will be a little lower if HSS tools with large side rake are used.

The programming steps for the HP 67 calculator are listed in Table 18. Two pre-programmed magnetic cards are provided the sponsor and are included in a separate mailing with the computer cards.

After the program is entered in the calculator, either by punching in the keystrokes listed in Table 18 or by using one of the pre-programmed cards, then the data is entered in the following manner:

1. Store the numerical value of the feed in register 1 (STO 1);

2. Store the numerical value of the depth of cut in register (STO 2);

3. Store the outside diameter (the inside diameter for boring) in register 3 (STO 3);

4. Store the spindle RPM in register 4 (STO 4).

To obtain the horsepower when cutting the 290 Brinell hardness steel, press the A key. Pressing the B key will give the horsepower when cutting the 200 Brinell hardness steel. The following example will illustrate this feature of the program.

4140 steel of 290 Brinell hardness is to be cut with a feed of 0.015 ipr, a depth of cut of 0.150" on an 8.5" diameter bar at a speed of 300 RPM. After the pre-programmed card is run through the calculator, the data are entered pressing the keys in the following sequence.

First: . 0 1 5 STO 1

Second: . 1 5 0 STO 2

Third: 8 . 5 STO 3

Fourth: 3 0 0 STO 4

Then press A to start the calculations. The answer will then be displayed as 23.1. That is, 23 horsepower will be needed for the above specified cutting conditions.

But what if the lathe only has an 18 HP motor? Then either the feed or the speed would have to be reduced. One method of doing this would be repeating the above example with smaller feeds until the one that resulted in 18 horsepower was found. However, this would be somewhat time consuming. To overcome this problem, the program listed in Table 18 makes it possible for the programmer to find directly the exact feed, or speed, that requires the specified horsepower. A second example will illustrate this method.

First, enter the data of the example once again and press the A key. The display will read 23.1 again. Now, to find the feed that corresponds to 18 HP, the 0.015 ipr feed is cleared (removed) from storage in register 1 by pressing the following keys: 0 STO 1. Now there is no feed stored in register 1. Next, press the A key. The calculator will run briefly and display 0. Finally, enter the required horsepower by pressing in sequence the keys 1 8 R/S. Note: the 18 is the required horsepower and the R/S key is an instruction to the calculator to run until the calculation is complete and then stop. In this case the answer is displayed as 0.0117.

In similar fashion, if a speed of 0 RPM were stored in register 4 instead of changing the feed, then the answer displayed would be 234. This is the RPM that would require 18 HP if the feed were 0.015 ipr and the depth equal to 0.150".

4.4 Chatter and vibration. It is impossible at the present time to predict whether chatter will occur during turning or boring operations because it depends upon too many unrelated factors such as: tool shape, conditions of the machine tool bearings, rigidity of the cross slide and tool

TABLE 18. Programming Steps for the Horsepower Required in Turning

001	*LBLA
002	4
003	.
004	0
005	3
006	STOI
007	GTOa
008	*LBLB
009	2
010	.
011	7
012	8
013	STOI
014	*LBLa
015	RCL1
016	X=0?
017	GTOb
018	×
019	RCL2
020	X=0?
021	÷
022	×
023	RCL3
024	X=0?
025	÷
026	×
027	RCL4
028	X=0?
029	GTOe
030	×
031	DSP1
032	RTN
033	*LBLb
034	R/S
035	RCLI
036	÷
037	RCL2
038	÷
039	RCL3
040	÷
041	RCL4
042	÷
043	DSP4
044	RTN
045	*LBLe
046	R/S
047	RCLI
048	÷
049	RCL1
050	÷
051	RCL2
052	÷
053	RCL3
054	÷
055	DSP0
056	RTN
057	R/S

holder, size and shape of the workpiece and microstructure of the workpiece. However, the following guidelines can help to overcome chatter problems when they do occur.

Generally, a reduction in the cutting force will reduce the tendency for chatter. The cutting force can be reduced by making the following changes in the tool shape: use as large a positive rake angle as possible, a smaller nose radius, a zero degree side cutting edge angle.

The cutting speed does not affect the cutting force significantly. However, in most cases a reduction in cutting speed will reduce the amount of chatter. In some cases, an increase in cutting speed is more beneficial.

5. OPTIMIZATION

5.1 Optimum tool life. The optimum tool life is defined as that tool life that results in either the minimum cost per part or else the maximum number of parts produced per day, depending upon which is considered more important. The tool life in this report is defined as the number of minutes of cutting time required for a flank wear of 0.060 inch for high speed steel tools or 0.020 inch for carbide tool to accumulate on the tool flank. The equations for the optimum tool life are derived in Datsko's Material Properties and Manufacturing Processes [2]. The two equations are:

1. $t_{mc} = (1/n - 1)(K_1/K_2 + t_{tc})$

2. $t_{mp} = (1/n - 1)t_{tc}$.

The symbols in the two equations are defined as follows:

t_{mc} is the tool life that gives the minimum machining cost.

t_{mp} is the tool life that results in the maximum production rate--that is, the greatest number of parts produced per day.

n is the slope of the cutting speed-tool life curve or the tool life exponent in the Taylor equation $vt^n = c$.

K_1 is the factory rate (direct plus overhead) expressed as $/min.

K_2 is the tool cost expressed as $/cutting edge.

t_{tc} is the tool changing or indexing time in minutes.

The values of n used in this program are: 0.065 for high speed steel; 0.205 for tungsten carbide; 0.40 for ceramic.

5.1.1 The HP 67 program. The complete program for the optimum tool life is listed in Table 19.

To run the optimum tool life program, follow the preliminary instructions listed under paragraph 4.1.1.1. After the program has been entered in the calculator, store the necessary operating conditions as listed below.

TABLE 19. Optimum Tool Life Program.

Line	Entry	Line	Entry	Line	Entry	Line	Entry
001	LBLA	010	.	019	STOD	028	÷
002	1	011	8	020	LBLE	029	RCL4
003	4	012	8	021	RCL2	030	+
004	.	013	STOD	022	RCL3	031	x
005	4	014	GTOE	023	÷	032	PRTX
006	STOD	015	LBLC	024	RCL1	033	RCLD
007	GTOE	016	1	025	6	034	RCL4
008	LBLB	017	.	026	0	035	x
009	3	018	5	027	÷	036	RTN
						037	R/S

Input	Entry
Factory rate ($/hour)	STO1
Tool Cost (Insert cost, $)	STO2
Number of edges per tool	STO3
Tool changing time (min.)	STO4

(The programmer can review the operating instructions in paragraph 4.1.1.2 if there are any questions concerning how the data is to be entered.)

After the operating conditions are stored in the calculator, the program is run by pressing A for a high speed steel tool, B for a carbide tool, or C for a ceramic tool. The calculator will then display the tool life for minimum cost for five seconds and then it will display the tool life for the maximum production rate.

If it is desired to rerun the program for a different set of operation conditions, it is necessary to simply store the new conditions in the appropriate registers and then press key A, B, or C again, depending upon which tool material is being used.

5.1.2 The Fortran program. The fortran program for calculating the optimum tool life for turning operations is included with the Fortran program that calculates the cutting conditions that result in the minimum machining cost. That program is described in paragraph 5.2.2.

5.2 Optimum Machining Cost. The computer software developed here is based on the fundamental machinability equation that is discussed in section 2 of this report. This program enables the NC machine programmer to select the optimum speed and feed from the ones that are available

on a given machine. The optimum speed and feed is the combination that results in the minimum machining cost. This optimization is done by constructing a matrix, or tabulation, of the unit cost (cost per operation) for each of the suitable combinations of feed and speed.

This analytical method of determining the optimum cutting speed and feed by means of the fundamental machinability equation is more reliable and efficient than the Ramberg [8] method because the latter is based on a statistical model with a relatively small number of samples. The variation of the inherent machinability of the workpieces from lot to lot can have a greater effect on the unit machining cost than modest changes in the cutting speed or feed alone. In order for the Ramberg [8] method to give reliable results, an extremely large number of parts would have to be machined for each combination of feed and cutting speed. But even if this were done it would not eliminate the variability in machinability of the parts from lot to lot.

The analytical method for optimization presented in this report is not based on a statistical model but instead it is based on well documented research that originated with Taylor's pioneering work [3] of 1907 up to the present. This analytical method is based on the following two universally accepted equations.

1. $Q = 12\ v\ f\ d$

Q is the rate of metal removal (cubic inches per minute) and determines the cutting time and cutting cost for a given turning operation. v, f, and d are the cutting speed, feed, and depth of cut respectively. This equation is valid for all turning and boring operations where the depth of cut is small compared to the diameter of the part.

The second equation is:

2. $v = K\ t^{-n} f^{-a} d^{-b}$

In this equation K is a tool and work material constant, t is the tool life, f is the feed, and d is the depth of cut. K, n, a, and b are experimentally determined constants. The average or typical values for the exponents when machining with tungsten carbide tools are: $n = 0.2$; $a = 2/3$; $b = 1/3$.

The second equation can be written as:

3. $v\ f^a = K\ t^{-n} d^{-b}$

If K, t, and d are kept constant for a given machining operation and if their product is identified as C then the equation can be simplified to:

4. $v\ f^a = C$ or $v\ f^{2/3} = C$

since the typical value of a is 2/3.

From this last equation it can be seen that the product of the speed times the feed raised to the 2/3 power is a constant. That is, for any increase in feed, the cutting speed has to be reduced by the feed ratio raised to the 2/3 power. For example, if the feed is doubled ($f_2 = 2\ f_1$), then the speed has to be reduced to 1/2 raised to the 2/3 power times the original speed. That is:

$$v_2 = (0.5)^{0.67} v_1 = 0.63\ v_1$$

In other words, if the feed is doubled (increased by 100%) in any turning operation, the cutting speed has to be reduced only 37% to maintain the same tool life.

By substituting these values into the first equation ($Q = 12\ v\ f\ d$), the advantage of always using the maximum possible feed for any machining operation is obvious. The rate of metal removal for the first case is:

$$Q_1 = 12\ v_1 f_1 d_1.$$

For the second case, the rate of metal removal for the same tool life and depth of cut is:

$$Q_2 = 12\ v_2 f_2 d_1.$$

If the second feed (f_2) is twice as large as the first feed ($f_2 = 2\ f_1$), and the second speed is 0.63 times v_1, then the rate of metal removal is:

$$Q_2 = 12(0.63\ v_1)(2\ f_1)d_1 = 15.12\ v_1 f_1 d_1.$$

Thus it can be seen that the rate of metal removal in the second case (Q_2) is 26% greater than the rate of metal removal in the first case (Q_1).

This is a trend that can always be expected if a large number of samples are tested. However, if only a few parts are machined then a premature failure of one or two tools can give misleading results.

Since the typical value for the depth of cut exponent b is 1/3, any change in the depth of cut requires that the cutting speed be changed by the same ratio raised to the 1/3 power. For example, if the depth of cut is doubled (100% increase) then the cutting speed has to be reduced to $(0.5)^{0.33}$ times the original or to 0.8 v_1. Thus doubling the depth of cut requires only a 20% reduction in cutting speed in order to maintain the same tool life. In this second case, the rate of metal removal Q_2 is 1.6 times the original metal removal rate Q_1. Thus by using one deep cut instead of two cuts with half the depth, the rate of metal removal is increased by 60%.

5.2.1 Procedure for optimizing cutting conditions. The method of optimizing the cutting speed and feed in this report is based both on the above concepts of metal removal rates and the fundamental machinability equation. The following operations or procedures have to be performed by the machine programmer and methods people in the same sequence that they are listed below in order to determine the optimum cutting conditions.

5.2.1.1 Tool material. The grade of tool material should be selected originally from the tables of recommended tool materials provided by the material manufacturers. However, after this optimization program is implemented and feed-back information is collected from the shop floor more reliable tables can be made by the programmers or methods people that list the relative performance of the same grade of tool material supplied by the different manufacturers.

In general, high speed steel tools should be used whenever it is not possible to operate the machine at a high speed, or when the machine has a low horsepower motor. In all other cases it is better to use a carbide or ceramic tool.

5.2.1.2 Tool shape. The following general recommendations should be considered when selecting style or shape of the cutting tool.

For economical machining, the nose radius is the most important feature of the tool shape. The metal removal

efficiency increases exponentially with an increase in the size of the nose radius. A zero nose radius is very inefficient, particularly with carbide tools.

It is possible to use larger nose radii with high speed steel tools than with carbide tools. The effect of the nose radius on the relative cutting speed when machining 2345 steel with high speed steel tools is illustrated in the following table:

nose radius (in)	0	1/32	3/64	1/8	3/16	1/4
relative speed (%)	100	130	143	186	204	218

A nose radius of 1/8" is very practical with high speed steel tools and it permits an increase of 86% in the cutting speed compared to the zero radius. Also, the surface finish of the machined part improves as the nose radius is increased. However, as the nose radius increases beyond 1/8" the tendency for chatter to occur increases.

The effect of the nose radius on the relative cutting speed when machining 4140 steel with C7 (K45) grade of carbide is illustrated in the following table:

nose radius (in)	0	1/64	1/32	3/64
relative speed (%)	100	290	360	410

As can be seen in the above table, the zero inch nose radius is very inefficient. The 1/64 inch nose radius is 2.9 times as good as (or 190% better than) the zero radius. The 1/32 inch radius is 23% better than the 1/64 inch radius and the 3/64 inch radius is 40% better than the 1/64 inch radius.

The side cutting edge angle (also called the entering angle or lead angle) also influences the relative cutting speed. The side cutting edge angle has the effect of reducing the chip thickness, which is equivalent to reducing the feed. The effect of the side cutting edge angle on the relative cutting speed has not been well documented. However, a 15 degree side cutting edge angle does permit a higher cutting speed than a zero degree angle; and a 30 degree angle is slightly better than a 15 degree angle.

The side rake angle also influences the relative cutting speed. An increase in the side rake angle first increases the relative cutting speed. This is true up to about 20 degrees for soft steel and 10 degrees for medium hardness steel. However, for very hard steel (45 or more

Rockwell C) the best side rake angle is zero degrees. For soft steel, as the side rake angle is increased beyond 20 degrees, the relative cutting speed decreases.

For soft and medium hard steel, a 5 or 6 degree positive rake insert has a slightly higher relative cutting speed than a 5 or 6 degree negative rake insert. However, since the negative rake tool has twice as many cutting edges, the cost per edge for the negative rake insert is about half that of the positive rake insert of the same size. In order to determine which is more economical it is necessary to calculate the total cost of the operation: the actual cutting cost plus the tool changing cost and the tool cost. This is done in the following programs of optimum machining costs in sections 5.2.2 and 5.2.3.

5.2.1.3 Depth of cut. Specify 1 roughing cut whenever possible rather than 2 or 3 shallow cuts. This will depend upon the amount of stock to be removed and the rigidity of the part.

5.2.1.4 Feed. Specify as large a feed as in consistent with surface finish requirements and part rigidity.

5.2.1.5 Cutting speed. The last step in specifying the cutting conditions is to select the cutting speed that gives the minimum cost or the maximum production rate for the operation being performed. This can be done by means of the computer programs listed in sections 5.2.2 and 5.2.3.

5.2.2 The HP-67 programs.

5.2.2.1 The Btc program. The Btc program makes it possible to determine the cutting speed and feed that will result in the minimum machining cost or maximum production rate for turning or boring operations. The input data for the Btc series are: length of cut, feed, depth of cut, spindle RPM, side cutting edge angle, side rake angle, back rake angle, nose radius, workpiece diameter, tool cost per edge. The registers that these data are stored in are shown in the following tabulation.

Input	Entry
Length of cut	STO0
Feed	STO1
Depth of cut	STO2
Spindle RPM	STO3
Side cutting angle	STO4
Side rake angle	STO5
Back rake angle	STO6
Nose radius	STO7
Work diameter	STO8
Tool cost per edge	STOE

Press A for grade C-5 and press B for grade C-7.

Four HP-67 programs were developed in this project for 4140 steel at four Brinell hardness levels: 200, 250, 290, and 320. Magnetic cards for these programs were also prepared and delivered to the sponsor.

The output of the Btc program is:

1. the tool life in minutes t.

2. the cutting time in minutes t_c.

3. the number of tools needed per part.

4. the machining cost in dollars per part.

The first three outputs are displayed on the calculator for only 5 seconds, while the fourth one is displayed until another run is made.

The machining cost includes the actual cutting cost, the tool cost, and the tool indexing cost. It does not include the loading and unloading cost or any other handling costs. The cost is based on a $30 per hour factory rate and 1 minute tool indexing time.

The complete program for the Btc series is given in Table 20 for the 290 Brinell hardness 4140 steel.

5.2.2.2 The BtD program. The BtD program is a modification of the Btc program. The BtD program has the provision built into it by means of which the original machinability relationships used in the Btc program can be corrected on the basis of feedback information from the shop floor. This is accomplished by using a correction factor G which is the ratio of the actual production tool

TABLE 20. Programming Steps for Btc Series.

Line	Entry	Line	Entry	Line	Entry	Line	Entry	Line	Entry
001	LBLE	043	RCLB	085	RCLA	127	RCL4	169	x
002	2	044	÷	086	.	128	D→R	170	RCL8
003	5	045	STOI	087	0	129	-	171	x
004	0	046	.	088	0	130	x	172	RCL3
005	STOA	047	2	089	1	131	+	173	x
006	.	048	CHS	090	3	132	RCL2	174	RCL9
007	0	049	RCLI	091	3	133	÷	175	X↔Y
008	0	050	X≤Y?	092	x	134	4	176	÷
009	2	051	GTO1	093	-	135	.	177	4
010	1	052	1	094	.	136	3	178	.
011	STOD	053	RCL1	095	2	137	8	179	8
012	2	054	X≤Y?	096	RCLA	138	x	180	8
013	1	055	GTO2	097	.	139	2	181	Y^x
014	.	056	4	098	0	140	.	182	PRTX
015	0	057	RCLI	099	0	141	3	183	STOI
016	STOB	058	X≤Y?	100	0	142	8	184	RCL0
017	RTN	059	GTO3	101	3	143	-	185	RCL1
018	LBLA	060	1	102	3	144	STx9	186	RCL3
019	GSBE	061	GTO4	103	x	145	.	187	x
020	3	062	LBL1	104	-	146	6	188	÷
021	5	063	.	105	RCLI	147	RCL1	189	P↔S
022	STO9	064	9	106	x	148	RCL2	190	PRTX
023	GTO9	065	GTO4	107	-	149	÷	191	STO0
024	LBLB	066	LBL2	108	LBL4	150	.	192	X↔Y
025	GSBE	067	.	109	STx9	151	0	193	÷
026	GSBE	068	6	110	RCL2	152	5	194	PRTX
027	4	069	RCLA	111	RCL7	153	CHS	195	STO1
028	0	070	.	112	1	154	Y^x	196	RCL0
029	STO9	071	0	113	RCL4	155	x	197	+
030	LBL9	072	0	114	SIN	156	STOC	198	2
031	RCL5	073	1	115	-	157	RCL1	199	÷
032	TAN	074	x	116	x	158	RCLD	200	RCLE
033	RCL4	075	-	117	-	159	+	201	RCL1
034	COS	076	RCLI	118	RCL4	160	RCLD	202	x
035	x	077	x	119	COS	161	Y^x	203	+
036	RCL6	078	1	120	÷	162	RCL2	204	P↔S
037	TAN	079	+	121	RCL7	163	RCLD	205	RTN
038	RCL4	080	GTO4	122	1	164	+	206	R/S
039	SIN	081	LBL3	123	.	165	1		
040	x	082	1	124	5	166	RCLC		
041	+	083	.	125	7	167	-		
042	TAN^{-1}	084	8	126	1	168	Y^x		

life over the theoretical calculated tool life. The input data and the registers they are stored in are listed below.

Input	Entry
Length of cut	STO0
Feed	STO1
Depth of cut	STO2
Spindle RPM	STO3
Side cutting angle	STO4
Side rake angle	STO5
Back rake angle	STO6
Nose radius	STO7
Work diameter	STO8
Tool cost per edge	STOE
Correction factor G	STOB

Press A for grade C-5 and press B for grade C-7.

Four HP-67 programs were developed in this project for 4140 steel at Brinell hardness levels of 200, 250, 290, and 320 since these are most common hardness values used in the sponsors shop. Magnetic cards for these programs were prepared and delivered to the sponsor.

The output of the BtD program is:

1. the tool life in minutes t.

2. the cutting time in minutes t_c.

3. the number of tools needed per part.

4. the machining cost in dollars per part.

The first three outputs are displayed in sequence on the calculator for 5 seconds. The fourth output is displayed until another run is made or the calculator is turned off.

The machining cost includes the actual cutting cost plus the tool cost and tool indexing cost. It does not include any of the handling costs. The cost is based on a factory rate of 30 dollars per hour and a 1 minute indexing time.

The complete program for the BtD series is given in Table 21 for the 290 Brinell hardness 4140 steel.

TABLE 21. Programming Steps for BtD Series.

Line	Entry	Line	Entry	Line	Entry	Line	Entry	Line	Entry
001	LBLE	044	P S	087	8	130	RCL4	173	RCL8
002	2	045	RCL5	088	RCLA	131	D→R	174	x
003	5	046	P S	089	.	132	−	175	RCL3
004	0	047	÷	090	0	133	x	176	x
005	STOA	048	STOI	091	0	134	+	177	RCL9
006	.	049	.	092	1	135	RCL2	178	X↔Y
007	0	050	2	093	3	136	÷	179	÷
008	0	051	CHS	094	3	137	4	180	4
009	2	052	RCLI	095	x	138	.	181	.
010	1	053	X<Y?	096	−	139	3	182	8
011	STOD	054	GTO1	097	.	140	8	183	8
012	2	055	1	098	2	141	x	184	Y^x
013	1	056	RCLI	099	RCLA	142	2	185	P↔S
014	.	057	X<Y?	100	.	143	.	186	RCLB
015	0	058	GTO2	101	0	144	3	187	P↔S
016	P⇄S	059	4	102	0	145	8	188	x
017	STO5	060	RCLI	103	0	146	−	189	PRTX
018	P S	061	X<Y?	104	3	147	STx9	190	STOI
019	RTN	062	GTO3	105	3	148	.	191	RCL0
020	LBLA	063	1	106	x	149	6	192	RCL1
021	GSBE	064	GTO4	107	−	150	RCL1	193	RCL3
022	3	065	LBL1	108	RCLI	151	RCL2	194	x
023	5	066	.	109	x	152	÷	195	÷
024	STO9	067	9	110	−	153	.	196	P↔S
025	GTO9	068	GTO4	111	LBL4	154	0	197	PRTX
026	LBLB	069	LBL2	112	STx9	155	5	198	STO0
027	GSBE	070	.	113	RCL2	156	CHS	199	X↔Y
028	4	071	6	114	RCL7	157	Y^x	200	÷
029	0	072	RCLA	115	1	158	x	201	PRTX
030	STO9	073	.	116	RCL4	159	STOC	202	STO1
031	LBL9	074	0	117	SIN	160	RCL1	203	RCL0
032	RCL5	075	0	118	−	161	RCLD	204	+
033	TAN	076	1	119	x	162	+	205	2
034	RCL4	077	x	120	−	163	RCLC	206	÷
035	COS	078	−	121	RCL4	164	Y^x	207	RCLE
036	x	079	RCL1	122	COS	165	RCL2	208	RCL1
037	RCLE	080	x	123	÷	166	RCLD	209	x
038	TAN	081	1	124	RCL7	167	+	210	+
039	RCL4	082	+	125	1	168	1	211	P↔S
040	SIN	083	GTO4	126	.	169	RCLC	212	RTN
041	x	084	LBL3	127	5	170	−	213	R/S
042	+	085	1	128	7	171	Y^x		
043	TAN^{-1}	086	.	129	1	172	x		

By means of the Btc or BtD programs it is possible to prepare a table of the machining costs for the several combinations of available cutting speeds and feeds and to select the minimum cost, or optimum, conditions. This is illustrated in section 5.3.

5.2.3 The Fortran program. The Fortran program developed under the addendum to the original project incorporates both the BtC and BtD described in sections 5.2.2.1 and 5.2.2.2 as well as the surface finish program described in section 4.2 and the horsepower requirements discussed in section 4.3.

The input data to run this program are:

1. Length of cut (inches).
2. Cutting diameter (inches).
3. Depth of cut (inches).
4. Feed (inches per revolution).
5. Spindle speed (revolutions per minute).
6. Tool material (C5 or C7 carbide).
7. Side cutting angle (degrees).
8. Side rake angle (degrees).
9. Back rake angle (degrees).
10. Nose radius (inches).
11. Tool cost (dollars per edge).
12. Tool indexing time (minutes).
13. Factory rate (dollars per hour).
14. Tool life correction factor.
15. Brinell hardness number of 4140 steel.

The tool life correction factor is always input as 1 (one) during the original programming of a production part. However, if it is found out from the feedback from the production shop that the tools are not lasting the

predetermined number of minutes then the program can be rerun entering the ratio of the actual tool life over the calculated tool life as the tool life correction factor. For example, if the calculated tool life is 30 minutes and the feedback from the production shop reports that the tools are actually lasting 45 minutes, then the tool life correction factor is 45/30 or 1.5. Now if the program is rerun in the future, the tool life correction factor should be input as 1.5 instead of 1.0.

The tool life correction factor can take care of unpredictable variables such as vibrations and rigidity of the machine tool or tool holders as well as work material variations.

The output of this Fortran program includes the following:

1. The tool life for minimum cost (minutes).

2. The tool life for maximum production (minutes).

3. The expected average tool life (minutes).

4. The cutting time per part (minutes).

5. The cost to make the cut (dollars).

6. The horsepower required.

7. The surface finish (micro-inches).

The cost to make the cut includes the cutting cost based on the inputed factory rate plus the tool cost and tool indexing cost.

Two sets of punched computer cards and two sets of the computer print-out of this Fortran program are submitted separately to the sponsor.

5.2.3.1 Instructions for operation of the program. The program can be run in the batch (stack of cards) mode without any modification except to set the program for the system available. The first 88 cards comprise the program proper. The cards that follow the RUN-LOAD card contain the required machining conditions for a given cut.

The 15 cutting conditions for any one cut have to be entered onto two input cards, the first 8 conditions on the

first card and the last 7 variables on the second card. The format for the correct input of the cutting conditions for this Fortran program is F 10.3. This means that the first pieces of input data (the first cutting condition) must fit in the first 10 spaces on the card; the second cutting condition must fit within the second ten spaces; etc. Also, a decimal point must be inserted after each cutting condition. For example, if a 44 inch long cut at a depth of 0.125 inches and with a feed of 0.010 ipr are to be programmed, then the input must be typed in as 44., 0.125, 0.010..

The order of placement on the data cards is as follows:

First card

Column	Data
1-10	Length of cut
11-20	Depth of cut
21-30	Feed
31-40	Spindle speed
41-50	Side cutting angle
51-60	Side rake angle
61-70	Back rake angle
71-80	Nose radius

Second card

Column	Data
1-10	Major diameter of cut
11-20	Factory rate
21-30	Tool changing time
31-40	Tool cost
41-50	Tool life correction factor
51-60	Brinell hardness
61-70	Tool grade (5.0 for C5; 7.0 for C7)

The program can produce multiple runs by stacking up several two card sets of data cards.

5.3 Examples of cost calculations.

5.3.1 Part number 10895621--piston tube. Table 22 summarizes the machining cost for operation number 151 (a roughing cut) on a piston tube for a variety of feeds and cutting speed. Line number 0 consists of the feed and cutting speed listed on the operation data sheet. The cost

TABLE 22. Machining Cost for Piston Tube.

Part No. [illegible] Name Piston Tube Material 4140 27C 2?7 HB

Dia. Start 3.5" Finish 3.127" Depth 0.186" Length 41" Tool C-7

Operation # 151 Machine tool Monarch lathe # 17612

Line No.	Feed ipr	Speed RPM	Insert	Angles	Cost/edge	Tool life (min)	Cut. time (min)	No. of tools	Unit Cost
0	0.0155	342	TNG 432	0-5-5	0.73	24.89	7.73	0.31	4.25
1	0.022	"	"	"	"	8.07	5.45	0.68	3.56
2	"	"	TNG433	"	"	11.82	5.45	0.46	3.29
3	0.0266	"	"	"	"	6.32	4.51	0.71	3.13
4	0.025	450	TNG434	15-5-5	"	3.52	3.64	1.04	3.10
5	0.0266	342	"	"	"	10.94	4.51	0.41	2.76
6	0.0307	"	"	"	"	6.83	3.91	0.57	2.66

of the carbide inserts were obtained from the Carboloy and Kennametal tool catalogs. The cutting cost was based on a 30 dollars per hour factory rate and 1 minute tool indexing time.

The estimated tool life is nearly 25 minutes and the actual chip-cutting time is 7.73 minutes. On this basis, each cutting edge can machine about three parts with a unit cost of $4.25. If the tool life is decreased by increasing the feed, the cutting cost can be reduced as discussed in section 5.2.

By increasing the feed to 0.022 ipr, the unit cost is reduced to $3.56 as shown on line 1. However, by increasing the nose radius on the tool from 2/64" to 3/64", each cutting edge can cut two parts and the unit cost is reduced to $3.29. Since 0.46 tools are used for each part, the feed can be increased even more. As shown in line 3, when the feed is increased to 0.0266 ipr the number of cutting edges per part is increased to 0.71 and the cutting cost is reduced to $3.13.

Lines 4, 5 and 6 illustrate how the cutting cost can be further reduced by increasing the nose radius to 4/64" and changing the side cutting edge angle from 0° to 15°. As shown in line 4, if the speed is raised to the next higher available speed of 450 RPM and the feed reduced to 0.025 ipr the cost is slightly reduced to $3.10. However, in this case the tool will not last long enough, on the average, to cut one piece since the tool life is 3.52 minutes and the actual chip cutting time is 3.64 minutes.

By increasing the feed and reducing the speed back to 342 RPM the cost can be reduced even further. Line 6 illustrates that if the feed is increased to 0.0307 ipr with a 4/64" radius insert, each cutting edge on the average will last for at least one part and the cutting cost is reduced to $2.66. This is a reduction of $1.59, or 37%, for each part.

Table 23 summarizes the machining cost for operation #181 (finish cut) of a piston tube. Line 0 contains the feed and cutting speed specified on the operation data sheet. Although the depth of cut is 0.050" for this finishing cut while the depth was 0.186" for the roughing cut, the feed and speed are the same on the operation data sheet. As shown on line 0, the cutting time is 7.73 minutes and the cutting cost is $3.87. Since the tool life is extremely long, a higher speed and feed can be used.

TABLE 23. Machining Cost for Piston Tube.

Part No. 10895621 Name Piston Tube Material 4140 270-297 HB

Dia. Start 3.127" Finish 3.027" Depth 0.050" Length 41" Tool C-7

Operation # 181 Machine tool Monarch lathe #17612

Line No.	Feed ipr	Speed RPM	Insert	Angles	Cost/edge	Tool life (min)	Cut. time (min)	No. of tools	Unit Cost ¢
0	0.0155	342	TNG 432	0-5-5	0.73	1670	7.73	0.005	3.87
1	0.0266	570	"	15-5-5	"	31.93	2.70	0.09	1.46
2	"	"	TNG 433	"	"	80.78	2.70	0.03	1.39
3	0.0307	"	TNG 434	"	"	111	2.34	0.02	1.20

By increasing the feed to 0.0266 and the speed to 570 RPM, the cutting time is reduced to 2.70 minutes and cost is lowered to $1.46. However, by increasing the nose radius to 3/64", the cost is lowered to $1.39. By using the same 4/64" nose radius insert that gave the best performance for operation #151, and with the same feed of 0.0307 ipr the speed of 570 RPM results in a cutting time of 2.34 minutes and a cost of $1.20 per part. This is a reduction of $2.67 or 69%.

5.3.2 Part number 1200766--recoil cylinder. The feed and cutting speed listed on the operation data sheet are shown on line 0 of Table 24. A special insert, P3-P10 was being tried out. Because it was purchased in very small quantities, the tool cost was very high. As a result, the unit machining cost is $8.39. However, if the special tool were purchased in large quantities, the tool cost would be reduced significantly. This condition is shown on line 1 where the machining cost is lowered to $7.62 per part.

Lines 2 through 9 show what the average machining cost is for a K45 grade insert under a variety of cutting conditions. The lowest machining cost with a TNG insert is $4.96 as shown in line 8. This is accomplished with a feed of 0.028 ipr, speed of 355 RPM and a 333 size insert. Although it is not shown in Table 24, the unit cost can be reduced even further if a 334 (4/16" nose radius) insert were used.

Line 9 illustrates that a TPG (positive side rake) insert is only slightly better than the TNG (negative side rake) insert. The positive rake insert has only 3 cutting edges per tool whereas the negative rake insert has 6 cutting edges per tool.

The reduction in cutting time as shown in Table 24 is 5.72 minutes per part; a reduction of 40%. The reduction in cost, assuming that the P3-P10 insert can be purchased for $4.50 in large quantities, is $2.73 per part.

5.3.3 Part number 10895646--cylinder. The machining cost for a variety of feeds and cutting speeds for this cylinder are shown in Table 25. Line number 0 lists the cutting conditions as specified on the operation data sheet. The unit cost is $7.54 when cutting under the specified conditions. Again, an increase in the feed rate can reduce the unit cost, and an increase in the nose radius can permit a significant increase in tool life.

TABLE 24. Machining Cost for Recoil Cylinder.

Part No. 12007666 Name Recoil Cylinder Material 4130 305-323 Hs

Dia. Start 4.0" Finish 3.825" Depth 0.088" Length 86.5" Tool P3-P10 C-7 (K45)

Operation # 200 Machine tool Fischer lathe

Line No.	Feed ipr	Speed RPM	Insert	Angles	Cost edge	Tool life (min)	Cut. time (min)	No. of tools	Unit Cost
—	—	—	—	P3-P10	Grade	insert	—	—	—
0	0.020	300	TPG 432	0,0,0	5.20	69.73	14.42	0.21	8.39
1	"	"	"	"	1.50	69.73	14.42	0.21	7.62
—	—	—	—	K-45	Grade	Insert	—	—	—
2	0.020	300	TNG 432	0-5-5	0.73	41.70	14.42	0.35	7.63
3	0.028	"	"	"	"	14.80	10.3	0.70	6.00
4	"	355	"	"	"	6.51	8.7	1.34	6.00
5	"	"	"	15-5-5	0.73	7.81	8.7	1.11	5.72
6	0.020	"	TNG 433	"	"	42.47	12.18	0.29	6.44
7	0.028	"	"	"	"	15.08	8.7	0.58	5.06
8	"	"	TNG 333	"	0.55	15.08	8.7	0.58	4.96
9	"	"	TPG 333	15,0,5	1.25	28.20	8.7	0.31	4.89

TABLE 25. Machining Cost for a Cylinder.

Part No. 10895646 **Name** Cylinder **Material** 4140 230-255 H_B

Dia. Start 8.5" **Finish** 8.250 **Depth** 0.125 **Length** 48 **Tool** C-7

Operation # 40 **Machine tool** American N/c lathe

Line No.	Feed ipr	Speed RPM	Insert	Angles	Cost/edge	Tool life (min)	Cut. time (min)	No. of tools	Unit Cost
0	0.0181	196	CNMG432	15-5-5	0.75	21.80	13.53	0.62	7.54
1	0.025	196	TNG433	"	0.73	13.08	9.80	0.75	5.82
2	0.0285	"	"	"	"	8.65	8.59	0.99	5.52
3	0.0333	168	"	"	"	11.25	8.58	0.76	5.23
4	"	"	TNG 333	"	0.55	11.25	8.58	0.76	5.09

Line 1 shows that by increasing the feed to 0.025 ipr and the nose radius to 3/64" results in an average machining cost of $5.82. Since the tool life is considerably greater than the cutting time, a further increase in the feed to 0.0285 reduces the unit cost to $5.52.

The results shown in line 3 demonstrate that sometimes a reduction in cutting speed accompanied with a corresponding increase in the feed results in a more efficient process. In this case, by reducing the speed to the next lower value (168 RPM) and increasing the feed to 0.0333 ipr, the unit cost is lowered to $5.23.

It is demonstrated in line 4 of Table 25 that using a smaller, less expensive, insert can reduce the machining cost even further. By using a TNG 333 insert instead of a TNG 433 insert, the unit cost is reduced by 14 cents to $5.09. This latter cost is $2.45, or 32%, less than the average cost associated with the specified cutting conditions.

5.3.4 Part number 10895646--cylinder--N/C. Table 26 summarizes the machining cost for a cylinder that is being turned on a Sunstrand numerical-controlled Omnilathe. Line number 0 contains the machining conditions that are listed on the operation data sheet. The average machining cost in this case is $7.26. This cost is relatively high because a very large, and therefore more expensive, insert is used and also because the tool life is relatively long.

By increasing both the feed and speed as shown in lines 1, 2, and 3, the machining cost can be lowered. However, line 4 shows that a speed of 250 RPM is less efficient than a speed of 200 RPM because of the increased tool cost.

Lines 5, 6, and 7 illustrate further reductions in the machining cost that result from using a smaller, less expensive, insert. As shown in line 5, the minimum machining cost is $4.66, which is $2.60 or 36% less than the average cost for the specified cutting conditions.

5.3.5 Part number 12007737--cylinder--N/C. Table 27 summarizes the machining cost when this cylinder is turned on an N/C lathe. Only the first two turning cuts are listed here since the data concerning the contouring cuts was incomplete. Line number 0 shows the specified feed and cutting speed as shown on the operation data sheet. A large expensive insert and a long tool life causes the unit

TABLE 26. Machining Cost for a Cylinder on an N/C Lathe.

Part No. 1089564б Name Cylinder Material 4140 250 HB

Dia. Start 8.5 Finish 8.250 Depth 0.125 Length 47 7/8 Tool C-7

Operation # 40 Machine tool Sunstrand Omnilathe - N/C

Line No.	Feed ipr	Speed RPM	Insert	Angles	Cost/edge	Tool life (min)	Cut. time (min)	No. of tools	Unit Cost $
0	0.018	190	SPG 634	15, 0, 5	1.80	124	14.00	0.11	7.26
1	0.025	200	"	"	"	33.78	9.58	0.28	5.44
2	0.030	"	"	"	"	19.01	7.98	0.42	4.96
3	"	210	"	"	"	14.98	7.60	0.51	4.97
4	"	250	"	"	"	6.40	6.39	1.0	5.49
5	"	200	SPG 424	"	1.10	19.01	7.98	0.42	4.66
6	"	"	SNG 434	15-5-5	0.50	10.31	7.98	0.77	4.76
7	"	"	SNG 424	"	0.40	10.31	7.98	0.77	4.69

TABLE 27. Machining Cost for a Cylinder on an N/C Lathe.

Part No. 12007737 Name Cylinder Material 4130: 297-332 HB

Dia. Start 5 3/8" Finish 5.250 Depth 0.094 Length 2 × 58.5 Tool C-7

Operation # 150 Machine tool N/C American lathe

Line No.	Feed ipr	Speed RPM	Insert	Angles	Cost/edge	Tool life (min)	Cut. time (min)	No. of tools	Unit Cost $
—	—	—	2 cuts	at 0.	094"	deep	—	—	—
0	0.012	190	TNMM542	15-5-5	1.75	447	25.66	0.06	12.96
1	0.025	200	"	"	"	35.62	11.70	0.33	6.59
2	0.025	250	TNG323	"	0.40	22.49	9.36	0.42	5.05
—	—	—	one	cut at	0.188"	deep	—	—	—
3	0.025	190	TNG323	15-5-5	0.40	12.40	12.32	0.99	7.05

machining cost to be high--$12.96 for each pass or $25.92 for the two passes. Line 1 shows that by increasing both the feed and speed, the cost can be reduced by 50%. Line 2 shows that by using a smaller insert and a larger speed, the cost can be further reduced to $5.05 per pass or $10.10 for the 2 passes. This is a saving of $14.82 or 57% per part.

However, if the two 0.094" depth of cuts were replaced with one 0.188" deep cut with a corresponding decrease in cutting speed, the machining cost is further reduced to $7.05 per part, compared to the original cost of $25.92.

The calculation shown in Tables 22 to 27 are not intended to show the optimum machining conditions because it is not known if even larger feeds or smaller inserts could be used. These facts can only be obtained by feedback from the production floor. These tables and the computer programs provided with this project are intended to help the machine programmer determine the best cutting conditions based on the known effects of tool shape and size of cut on the cutting speed-tool life relationship.

Whenever it is found that the actual tool life in the production shop does not agree with the values obtained from the first run of the computer program, then the tool life correction factor should be changed from 1.0 to the numerical value of the ratio of the actual tool life over the calculated tool life. All future use of the computer program for that part should include the new tool life correction factor.

6. CONCLUSIONS AND RECOMMENDATIONS

The computer programs developed during this project are of particular value to N/C programmers, methods and standards analysts, production planners/estimators, tool engineers, and other related manufacturing shop personnel.

Based on tests and evaluations in production applications, with 4140 steel, the computerized control method for turning surpasses the use of existing tabulated data banks in:

a. quickly and accurately providing machining parameters

b. providing flexibility to interrelate physical machining parameters

c. analyzing effects of variable parameters on time and costs

d. adjusting machining parameters to actual workpiece/cutting tool/machine tool conditions, and

e. setting optimal parameters for maximum production and/or minimum cost operation.

It is recommended that the stepwise instructions presented in this report be implemented when establishing and optimizing metal cutting parameters.

REFERENCES

1. Machinability Data Center, Machining Data Handbook, Second edition, 1972.

2. Datsko, J., Material Properties and Manufacturing Processes, John Wiley and Sons, Inc., New York, 1966.

3. Taylor, F. W., On the Art of Cutting Metals, Trans. ASME, 28, 1907.

4. ASME, Manual on Cutting of Metals, ASME, 1952.

5. Henkin, A. and Datsko J., The Influence of Physical Properties on Machinability, ASME Trans., Series B, Vol. 85, No. 4, Nov. 1963, p. 321.

6. Boston, O. W., Metal Processing, John Wiley and Sons, Inc., New York, 1951.

7. Datsko, J., Materials in Design and Manufacturing, Malloy, Inc., Ann Arbor, Michigan, 1977.

8. Ramberg, J. C., Development and Adaptation of a Control System for Optimization of Single and Multiple Operation Machining, June 1974, No. R-CR-74-031.

9. ASM, Machining: Vol. 3, ASM Handbook, 1969.

APPENDIX A

Appendix A. Fortran program for the cutting speed.

The following tabulation is a copy of the print-out of the Fortran program for the Basic Machinability Equation. The complete program is listed on lines 1 through 145 in Table A-1. The 15 input data points are listed and defined in Table A-2 of Appendix A. Typical runs using this program are shown in Tables A-3 and A-4 of this Appendix. At the top of Table A-3 is the list of the data fed into the program for a T-1 high speed steel tool. The print-out of the computer calculations constitutes the bottom half of Table A-3. The numerical values of the seven individual tool and environment constants are printed out as well as the combined tool factor A. The strain strengthening factor y, the feed exponent a, the size of cut constant q, and the work material constant B are all printed out. In addition the machinability index, the B/q ratio, of the material for the given cutting conditions is also printed out. Finally the recommended cutting speed in fpm is given. In this case the answer is 124 fpm which compares very favorably with the value of 120 fpm that was obtained experimentally.

Table A-4 of Appendix A is the print-out sheet for a run of the computer program for C-7 (K45) carbide. In this case the recommended cutting speed is 619 fpm, which also is in close agreement with the experimentally obtained value of 600 fpm.

AD-A088 416 MICHIGAN UNIV ANN ARBOR DEPT OF MECHANICAL ENGINEERING F/G 13/8
AUTOMATED PROCESS CONTROL FOR MACHINING (CAM).(U)
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TABLE A-1. Main Fortran Program

```
      PRINT 1
      FORMAT('1THIS PROGRAM IS DESIGNED  FOR THE CAM PROJECT'////)
      PRINT 30
      FORMAT ('AF: THE CUTTING FLUID CONSTANT'//)
      PRINT 31
      FORMAT (' AM: THE TOOL MATERIAL CONSTANT'//)
      PRINT 2
      FORMAT(' AR6:PERCENT AREA REDUCTION AT 600 DEGREE F'//)
      PRINT 80
      FORMAT('BR:BACK RAKE ANGLE-DEGREES'//)
      PRINT 3
      FORMAT('D:DEPTH OF CUT-INCHES'//)
      PRINT 4
      FORMAT(' ER:EFFECTIVE RAKE ANGLE-DEGREES'//)
      PRINT 5
      FORMAT('F: FEED RATE-INCHES PER REVOLUTION'//)
      PRINT 6
      FORMAT('H:RADIUS OF THE WORKPIECE,THE WALL THICKNESS OF TUBING
     1,OR THE THICKNESS OF A PLATE-INCHES'//)
      PRINT 7
      FORMAT(' HB6:BRINELL HARDNESS NUMBER AT 600 DEGREE F'//)
      PRINT 8
      FORMAT(' ZK6:THERMAL CONDUCTIVITY AT 600 DEGREE F-BTU/HR/FT/F'//)
      PRINT 9
      FORMAT(' ZM:STRAIN STRENGTHENING EXPONENT'//)
      PRINT 10
      FORMAT(' R: NOSE RADIUS OF THE TOOLBIT-INCHES'//)
      PRINT 11
      FORMAT(' SCE:SIDE CUTTING EDGE ANGLE-DEGREES'//)
      PRINT 81
      FORMAT(' SR: SIDE RAKE ANGLE-DEGREES'//)
      PRINT 12
      FORMAT(' T: DESIRED TOOL LIFE-MINUTES'//)
      PRINT 22
      FORMAT('1DATA$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$'//)
      READ 15,J
      FORMAT(I3)
      IF (J.EQ.000) GO TO 900
      READ 20,T,HB6,SR,R,SCE,D,F,H,ZK6,AR6,ZM,BR
      FORMAT(12F10.0)
      ER=57.2958*ATAN(TAN(.0174*SR)*COS(.0174*SCE)+TAN(.0174*BR)*SIN
     1(.0174*SCE))
      PRINT 24,T,F,HB6,H,ER,ZK6,R,AR6,SCE,ZM,D,BR,SR
      FORMAT(' T=',F9.5,T40,' F=',F9.5//' HB6=',F9.5,T40,' H=',F9.5//
     1' ER=',F9.5,T40,' ZK6=',F9.5//' R=',F9.5,T40,'AR6=',F9.5//' SCE='
     2,F9.5,T40,'ZM=',F9.5//'D=',F9.5,T40,' BR=',F9.5//' SR=',F9.5)
      ERC=46.-.1*HB6
      ZLCE=R*(1.571-.0175*SCE)+(D-R*(1-SIN(.0174*SCE)))/COS(.0174*SCE)
      TO CALCULATE THE TOOL MATERIAL CONSTANT
              HIGH SPEED STEEL TOOL***TUNGSTEN CARBIDE TOOL***CERAMIC
COL
      IAM=            1                       2                      3
      AT=30*(T**(-0.065))
      READ 45,IAM,IAF
      FORMAT(2I1)
```

TABLE A-1. Main Fortran Program continued

```
GO TO (51,52,53),IAM
AM=1.
PRINT 16
FORMAT('0***TOOL MATERIAL:HIGH SPEED STEEL T-1 OR M-1')
AC=(ABS(ZLCE/D))**.67
GO TO 101
AM=4.5*(T**(-.14))
PRINT 17
FORMAT('0***TOOL MATERIAL:TUNGSTEN CARBIDE C7 OR K45')
AC=4.38*ZLCE/D-2.38
GO TO 101
AM=6.*(T**(-.32))
PRINT 18
FORMAT('0***TOOL MATERIAL: CERAMIC')
AC=(ABS(ZLCE/D))**.67
IF(ER/ERC.LE.(-.2))GO TO 54
IF(ER/ERC.GT.(-.2).AND.ER/ERC.LE.1.)GO TO 55
IF(ER/ERC.GT.1..AND.ER/ERC.LE.4.)GO TO 56
IF(ER/ERC.GT.4.)GO TO 57
AE=.9
GO TO 102
AE=1.+((.6-.001*HB6)*(ER/ERC))
GO TO 102
AE=1.8-.00133*HB6-((.2-.00033*HB6)*ER/ERC)
GO TO 102
AE=1.0
AH=(H/2)**.25
         TO CALCULATE THE CUTTING FLUID CONSTANT
                DRY***HEAVY OIL***LIGHT OIL***WATER BASE
          IAF=  1           2           3           4
GO TO (61,62,63,64),IAF
AF=1.
PRINT 110
FORMAT('0***CUTTING FLUID:DRY OR FLOOD COOLANT')
GO TO 103
AF=1.1
PRINT 112
FORMAT('0***CUTTING FLUID:HEAVY OIL')
GO TO 103
AF=1.15
PRINT 111
FORMAT('0***CUTTING FLUID:LIGHT OIL')
GO TO 103
AF=1.25
PRINT 113
FORMAT('0***CUTTING FLUID:WATER BASE')
AS=1.00
B=ZK6/HB6*(SQRT(1-AR6/100))
Y=.0055*(SQRT(ZM))
A=.6*(F/D)**(-.05)
Q=(F+Y)**A*(D+Y)**(1-A)
AX=AF*AT*AM*AE*AC*AH*AS
VX=AX*(B/Q)
PRINT65
FORMAT('0CALCULATION $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$'//)
```

TABLE A-1. Main Fortran Program continued

```
PRINT 66,AT
FORMAT(' THE TOOL LIFE CONSTANT..............AT=',F9.3)
PRINT67,AM
FORMAT(' THE TOOL MATERIAL CONSTANT.........AM=',F9.3)
PRINT 68,AE
FORMAT(' THE EFFECTIVE RAKE ANGLE CONSTANT..AE=',F9.3)
PRINT 69,AC
FORMAT(' THE LENGTH OF CUTING EDGE CONSTANT AC=',F9.3)
PRINT 70,AF
FORMAT(' THE CUTTING FLUID CONSTANT.........AF=',F9.3)
PRINT 72,AH
FORMAT(' THE WORK PIECE SIZE CONSTANT.......AH=',F9.3)
PRINT 71,AS
FORMAT(' THE SURFACE FACTOR CONSTANT........AS=',F9.3)
PRINT 77,AX
FORMAT(' THE TOOL ENVIRONMENT FACTOR........AX=',F9.3//)
PRINT 74,Y
FORMAT(' THE STRAIN STRENGTHENING FACTOR.....Y=',F9.3)
PRINT 75,A
FORMAT(' THE SIZE OF CUT EXPONENT............A=',F9.3)
PRINT 76, Q
FORMAT(' THE SIZE OF CUT CONSTANT............Q=',F9.3//)
PRINT 73,B
FORMAT(' THE WORK MATERIAL PROPERTY CONSTANT B=',F9.3//)
P=B/Q
PRINT 78,P
FORMAT(' RATIO..........................B/Q =',F9.3)
PRINT 90
FORMAT('0 RESULT $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$'//)
PRINT 91,VX
FORMAT(' THE RECOMMENENDED CUTTING VELOCITY IS VX=',F9.3,' FPM')
GO TO 13
PRINT 901
FORMAT('0RUNNING OUT OF DATA      ')
STOP
END
```

TABLE A-2. List of the Input Data for the Fortran Program

AF: THE CUTTING FLUID CONSTANT

AM: THE TOOL MATERIAL CONSTANT

AR6:PERCENT AREA REDUCTION AT 600 DEGREE F

BR:BACK RAKE ANGLE-DEGREES

D:DEPTH OF CUT-INCHES

ER:EFFECTIVE RAKE ANGLE-DEGREE

F: FEED RATE-INCHES PER REVOLUTION

H:RADIUS OF THE WORKPIECE,THE WALL THICKNESS OF TUBING

HB6:BRINELL HARDNESS NUMBER AT 600 DEGREE F

ZK6:THERMAL CONDUCTIVITY AT 600 DEGREE F-BTU/HR/FT/F

ZM:STRAIN STRENGTHENING EXPONENT

R: NOSE RADIUS OF THE TOOLBIT-INCHES

SCE:SIDE CUTTING EDGE ANGLE-DEGREES

SR: SIDE RAKE ANGLE-DEGREES

T: DESIRED TOOL LIFE-MINUTES

TABLE A-3. Typical Run From the Fortran Program for a HSS Tool

```
DATA$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

T= 60.00000                                    F=  0.00800

HB6=250.00000                                  H=  2.00000

ER= 15.44399                                  ZK6= 21.50000

R=  0.04700                                   AR6= 29.64999

SCE= 15.00000                                 ZM=  0.11000

D=  0.09000                                     BR=  8.00000

SR= 14.00000

***TOOL MATERIAL:HIGH SPEED STEEL T-1 OR M-1
***CUTTING FLUID:FLOOD COOLANT OR WATER BASE

CALCULATION $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

THE TOOL LIFE CONSTANT.............AT=   22.990
THE TOOL MATERIAL CONSTANT.........AM=    1.000
THE EFFECTIVE RAKE ANGLE CONSTANT..AE=    1.257
THE LENGTH OF CUTING EDGE CONSTANT AC=    1.203
THE CUTTING FLUID CONSTANT.........AF=    1.000
THE WORK PIECE SIZE CONSTANT.......AH=    1.000
THE SURFACE FACTOR CONSTANT........AS=    1.000
THE TOOL ENVIRONMENT FACTOR........AX=   34.771


THE STRAIN STRENGTHENING FACTOR.....Y=    0.002
THE SIZE OF CUT EXPONENT............A=    0.677
THE SIZE OF CUT CONSTANT............Q=    0.020


THE WORK MATERIAL PROPERTY CONSTANT B=    0.072


RATIO..............................B/Q =    3.569

 RESULT $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

THE RECOMMENEDED CUTTING VELOCITY IS VX=  124.081 FPM
```

TABLE A-4. Typical Run From the Fortran Program for C-7 Grade of Carbide Tool

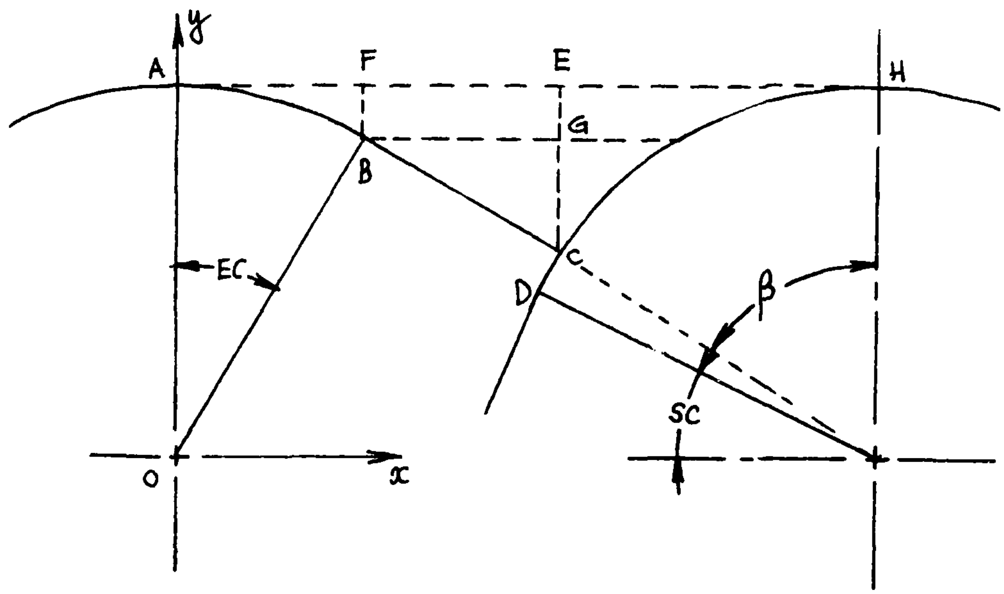
```
DATA$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

T= 60.00000                                  F=  0.00800

HB6=250.00000                                H=  2.00000

ER= -4.98473                                 ZK6= 21.50000

R=  0.04700                                  AR6= 29.64999

SCE=  0.0                                    ZM=  0.11000

D=  0.09000                                  BR= -5.00000

SR= -5.00000

***TOOL MATERIAL:TUNGSTEN CARBIDE C7 OR K45
***CUTTING FLUID:FLOOD COOLANT OR WATER BASE

CALCULATION $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

THE TOOL LIFE CONSTANT..............AT=   22.990
THE TOOL MATERIAL CONSTANT..........AM=    2.537
THE EFFECTIVE RAKE ANGLE CONSTANT..AE=    0.900
THE LENGTH OF CUTING EDGE CONSTANT AC=    3.306
THE CUTTING FLUID CONSTANT..........AF=    1.000
THE WORK PIECE SIZE CONSTANT........AH=    1.000
THE SURFACE FACTOR CONSTANT.........AS=    1.000
THE TOOL ENVIRONMENT FACTOR.........AX=  173.527

THE STRAIN STRENGTHENING FACTOR.....Y=     0.002
THE SIZE OF CUT EXPONENT............A=     0.677
THE SIZE OF CUT CONSTANT............Q=     0.020

THE WORK MATERIAL PROPERTY CONSTANT B=     0.072

RATIO.............................B/Q =     3.569

 RESULT $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

THE RECOMMENENDED CUTTING VELOCITY IS VX=  619.240 FPM
```

APPENDIX B

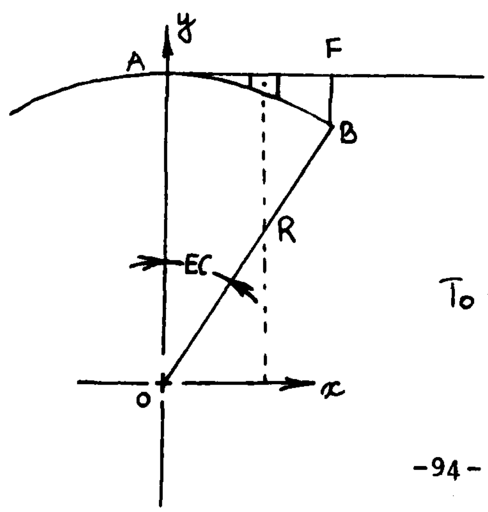
APPENDIX B

Derivation of Equations for the Theoretical Surface Finish

FORMULA FOR $2R\sin EC < FEED < 8R$,EC 6^{o},SC 15^{o}



To find the mean line of ABCHEF , divide the figure into four sections as shown above.The following are calculations for each segment.



$x_F = R\sin EC$

$BF = R(1-\cos EC)$

To find the mean line of AFB

$\bar{y}_1 a_1 = \int y\,da$

Let $\bar{y}$ and $\mathcal{A}$ be the mean line and total area of the whole contour. By defifition:

$$\bar{y}\mathcal{A} = \bar{y}_1\mathcal{A}_1 + \bar{y}_2\mathcal{A}_2 + \bar{y}_3\mathcal{A}_3 + \bar{y}_4\mathcal{A}_4$$

$$\mathcal{A} = \mathcal{A}_1 + \mathcal{A}_2 + \mathcal{A}_3 + \mathcal{A}_4$$

equation of $\widehat{AB}$: $x^2 + y^2 = R^2 \qquad 0 \leq x \leq R\sin EC$

equation of $\overline{BC}$: for $R\sin EC \leq x \leq x_c$

$$y = -(tg\, EC)x + R\cos EC + R\,tg\, EC \sin EC$$

equation of $\widehat{CH}$:

$$y^2 + (x-f)^2 = R^2 \qquad x_c \leq x \leq f$$

The Result

The Root Mean Square for EC 6°, SC 15° and $2R\sin EC < \text{feed} < 8R$ is given by:

$$\underset{i=1,n}{RMS} = \left\{ \frac{1}{n}\sum_{x_i=0}^{R\sin EC}\left(\sqrt{R^2-x_i^2} - \bar{y}\right)^2 + \frac{1}{n}\sum_{x_i=R\sin EC}^{x_c}\left[-(tg\,EC)x + R\cos EC + R\,tg\,EC\sin EC - \bar{y}\right]^2 + \frac{1}{n}\sum_{x_i=x_c}^{f}\left(\sqrt{-(x_i-f)^2+R^2} - \bar{y}\right)^2\right\}^{.5}$$

$$y_1 \mathcal{A}_1 = \int_0^{R\sin EC} \frac{R + \sqrt{R^2 - x^2}}{2} \left(R - \sqrt{R^2 - x^2}\right) dx$$

$$= \int_0^{R\sin EC} \frac{x^2}{2}\, dx \quad = \frac{R^3 \sin^3 EC}{6}$$

Area of AFB : $\mathcal{A}_1 = \frac{1}{2}\left(FB + AO\right) AF -$ area of (OAB)

$$\mathcal{A}_1 = \frac{R(1 - \cos EC) + R}{2} R\sin EC - R^2 \frac{EC}{2}$$

where EC is in radian

$$\mathcal{A}_1 = R^2\left(\sin EC - \frac{\sin 2EC}{4} - \frac{EC}{2}\right)$$

$$\bar{y}_1 = \frac{R^3 \sin^3 EC}{6 \mathcal{A}_1} = \frac{R \sin^3 EC}{6\left(\sin EC - \frac{1}{4}\sin 2EC - \frac{EC}{2}\right)}$$

To find coordinate of C , $\{C\} = (BC) \cap (CH)$

equation of $\overline{BC}$: $y = (-tg\, EC)x + R\cos EC + R\, tg\, EC \sin EC$

equation of $\widehat{HD}$: $y^2 + (x - f)^2 = R^2$

substitute y into 2^{nd} equation

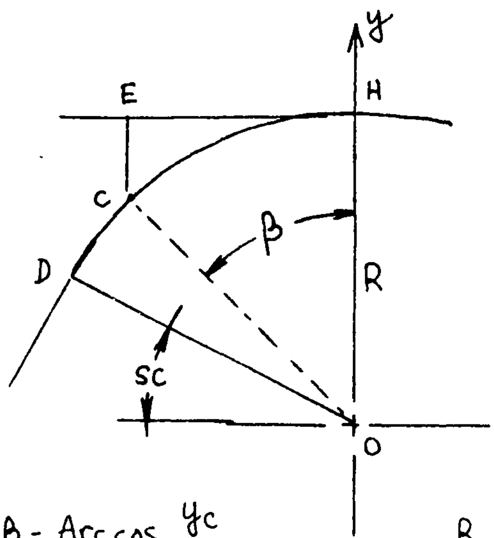
$$\left(tg^2 EC+1\right)x^2 - 2\left[tg\,EC\left(R\cos EC + R\,tg\,EC\sin EC\right)+f\right]x + \left(R\cos EC + R\,tg\,EC\sin EC\right)^2 + f^2 - R^2 = 0$$

Solve this equation, with $x_c < f$, and let

$$B = tg\,EC\left(R\cos EC + R\,tg\,EC\sin EC\right) + f$$

$$x_c = \frac{1}{tg^2 EC+1}\left\{B - \left[B^2 - \left(tg^2 EC+1\right)\left[\left(R\cos EC + R\,tg\,EC\sin EC\right)^2 + f^2 - R^2\right]\right]^{0.5}\right\}$$

so, $y_c = -\left(tg\,EC\right)x_c + R\cos EC + R\,tg\,EC\sin EC$



$\beta = \text{Arccos}\,\dfrac{y_c}{R}$ β is in radian

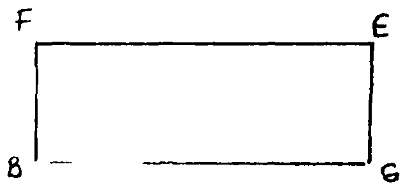
By symmetry, the area and the mean line are

$$a_3 = \frac{R(1-\cos\beta)+R}{2}\,R\sin\beta - R^2\frac{\beta}{2}$$

$$= R^2\left(\sin\beta - \frac{1}{4}\sin 2\beta - \frac{\beta}{2}\right)$$

$$\bar{y}_3 = \frac{R\sin^3\beta}{6\left(\sin\beta - \frac{1}{4}\sin 2\beta - \frac{\beta}{2}\right)}$$

Note : We simply change EC into β in equations for a_1 and $\bar{y}_1$ to get a_3 and $\bar{y}_3$



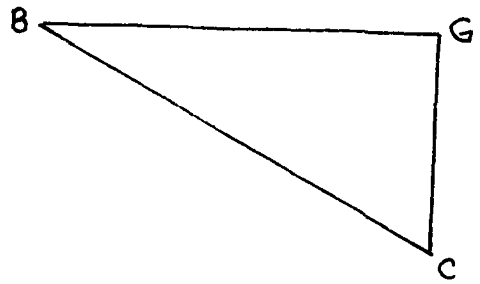
$$a_2 = BF \times FE$$

$$= R(1-\cos EC)(x_c - R\sin EC)$$

$$\bar{y}_2 = \frac{R}{2}(1+\cos EC)$$

$$\bar{y}_2 a_2 = R(1-\cos EC)(x_c - R\sin EC)\frac{R}{2}(1+\cos EC)$$

$$= \frac{R^2}{2}\sin^2 EC\,(x_c - R\sin EC)$$



$$\mathcal{a}_4 = \frac{1}{2} BG \times GC$$

$$= \frac{1}{2}\left(x_c - R\sin EC\right)\left(R\cos EC - y_c\right)$$

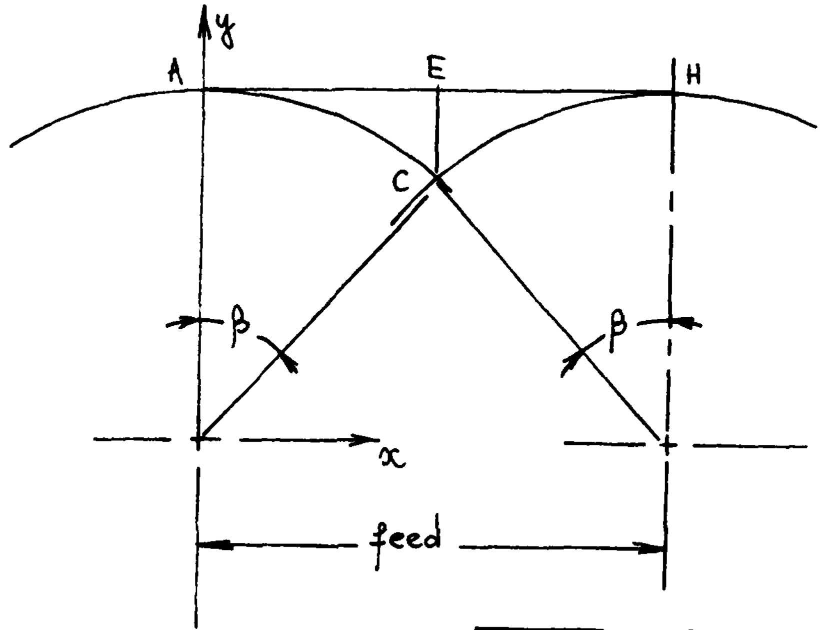
$$\bar{y}_4 = y_c + \frac{2}{3} CG = y_c + \frac{2}{3}\left(y_G - y_c\right)$$

$$= \frac{1}{3}\left(y_c + 2y_G\right)$$

$$= \frac{1}{3}\left(y_c + 2R\cos EC\right)$$

$$\bar{y}_4 \, \mathcal{a}_4 = \frac{1}{6}\left(x_c - R\sin EC\right)\left(R\cos EC - y_c\right)\left(y_c + 2R\cos EC\right)$$

FORMULA FOR $0 \leqslant \text{feed} \leqslant 2R\sin EC$, $EC = 6^\circ$, $SC = 15^\circ$



$x_c = f/2 \qquad y_c = \sqrt{R^2 - x_c^2} = \sqrt{R^2 - f^2/4}$

$\beta = \text{Arccos}\, \dfrac{y_c}{R} \qquad \beta$ is in radian

By symmetry, the mean line for ACE is also the mean line for ACHE. From previous calculations:

$$\bar{y}\,a = \frac{R^3 \sin^3\beta}{6} \qquad a = R^2\left(\sin\beta - \frac{1}{4}\sin 2\beta - \frac{\beta}{2}\right)$$

$$\bar{y} = \frac{R\sin^3\beta}{6\left(\sin\beta - \frac{1}{4}\sin 2\beta - \frac{\beta}{2}\right)}$$

Formula for the Root Mean Square ,with $EC = 6^{\circ}$, $SC = 15^{\circ}$

and $0 \leqslant feed \leqslant 2RsinEC$ is given by:

$$\underset{i=1,n}{RMS} = \left\{ \frac{1}{n} \sum_{x_i=0}^{x_c} \left(\sqrt{R^2 - x_i^2} - \bar{y} \right)^2 \right\}^{0.5}$$

We have just presented two formulas for RMS. In each case,all angles must be in radian,and all lengths must be in micro inch lengths.

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Turning cuts were made on 4140 steel at 200 and 290 Brinell hardness with HSS and carbide tools. Computer programs were prepared for both Fortran and hand-held computers to calculate the cutting speed for turning. The programs were based on a Fundamental Machinability Equation that includes the tool material and shape, the size of cut and size of the workpiece. Programs were also written for surface finish and horsepower requirements, and for time and cost analyses and control.

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